Landfill Covers for Use at Air Force Installations

February 1999

Prepared for:
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Executive Summary

During the 1960s, the advent of the environmental era in the United States brought with it a new appreciation for the adverse and chronic effects of past solid waste disposal practices. As a result, a massive amount of legislation was enacted with the intention of preventing and mitigating pollution at landfill sites. Today, both the technical design of landfills and the applicable regulatory requirements are complex, resulting in high costs for landfill remediation.

The Air Force is currently responsible for about 600 landfills, of which approximately 375 have not been remediated. Because of the expense and risk associated with treating or removing these wastes, they are usually contained in place, which requires the construction of a suitable cover. Therefore, the construction of a cover is likely to be identified as the optimal remedial action for most of these landfills.

Although Air Force landfills contain primarily wastes that are similar to municipal solid waste, they have characteristics that set them apart from ordinary landfills:

- About 80 percent have been inactive for more than 20 years.
- Less than 1 percent have liners below the waste.
- The average size is only 13.3 acres.
- They are old, so that much of the waste has decomposed and consolidated, and little gas is being produced.

Typical construction costs for conventional covers on Air Force landfills vary from $318,000 to $571,000 per acre; therefore, the costs for a single landfill cover at an Air Force installation is typically in the millions of dollars.

There are at least four important incentives for the Air Force to obtain up-to-date information on the design and construction of landfill covers:

- Federal and state statutes mandate that each Air Force landfill must be identified for no further action, remediated, or removed.
- Each landfill creates a potential risk to human health and the environment.
- Designing and constructing an effective landfill cover is complex and requires a team of engineers and scientists with a broad knowledge base.
- Conventional landfill covers are expensive, and the Air Force needs more cost-effective alternative covers that meet remediation requirements.

A primary objective of this report is to provide the Air Force with state-of-the-art information and references from the current literature on the governing regulations, selection, design, and construction of landfill covers. This material will help identify more cost-effective approaches and reduce remediation costs. This document is part of a series that focuses on landfill covers. Other documents will (1) identify and characterize the current inventory of Air Force landfills, (2) provide a screening tool for the selection of landfill cover alternatives, (3) provide a guidance document for remedial investigations, and (4) evaluate computer models that may be useful for landfill cover design.

The principal sections of this report concern the regulatory framework surrounding landfill covers and the technical basis for landfill cover design and construction. The report discusses conventional cover designs currently in use and innovative design concepts that have become available during the past decade. Some of these innovative cover designs have the potential to be effective at many Air Force landfills and result in a significant reduction in remediation costs.

Although the Resource Conservation and Recovery Act (RCRA) is the controlling federal law for both municipal solid waste and hazardous waste landfills, the remediation of old Air Force landfills is also addressed under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). RCRA, however, remains the source of potential Applicable or Relevant and Appropriate Requirements (ARARs) that are applied as cleanup criteria under CERCLA. State rules and regulations also apply at Air Force landfills.

The intimate association among CERCLA, RCRA, and state regulations can pose an impediment to the selection and installation of alternative, cost-effective landfill covers because of the prescriptive nature of both RCRA and state regulations. Regulations are often blindly followed without considering innovative technologies that can provide an environmentally responsible solution at considerable cost savings. However, the association among the various regulations also provides the latitude to install alternative covers under the CERCLA process because of the flexibility in selecting ARARs. The Environmental Protection Agency, the states, and the Department of Defense are fully aware of this dichotomy and have expended considerable effort in defining and supporting the role of innovative technologies in the nation’s remediation programs. This report lays the groundwork for understanding this flexibility and the complexity of the existing rules and regulations. It provides resources for the development and application of innovative technologies.

Remedial project managers need to know how modern landfill covers are designed and constructed, how they can be expected to perform, and what design options are available to them. They can find the following information in the technical section of this report:

- Site-specific aspects of landfill cover selection and design
- Landfill covers and their components
- Landfill cover design elements
- Case studies of landfill cover performance

Site characteristics that have a dominant influence on choosing an appropriate final cover include climate, available soils, landfill characteristics, hydrogeology, gas production, seismic environment, and land reuse. Design elements that should be considered in planning a landfill cover include water balance, gas control, slope stability, and erosion control.

Nearly all landfill covers in place today are *conventional, barrier-type landfill covers.* They are often accepted as presumptive remedies but are expensive to construct and maintain. These designs place a barrier layer within the cover that is intended to prevent water from moving downward into the waste in response to the force of gravity. Compacted clay and synthetic materials are common components within barrier-type covers. These covers may be used in all climates and are especially appropriate for use where precipitation equals or exceeds evaporation demand. It should be noted that even though they are widely accepted by regulators and others, it is clear that these barriers are not impermeable and that their performance can be expected to degrade with time.

The subtitle D cover—a modified barrier cover that is also called a compacted soil cover—is often accepted by regulators for use on landfills containing municipal solid waste. Therefore, it should be acceptable on many Air Force landfills, particularly in regions where evaporation equals or exceeds precipitation. These covers are significantly less expensive to build than conventional barrier-type covers and should be considered for Air Force landfills. Because the barrier is moderately permeable and the soil layer has limited water-holding capacity, these covers may be less effective than alternative covers.

While some innovative cover systems rely upon the barrier concept, others do not. Innovative covers include capillary barriers, dry barriers, asphalt barriers, soil-plant covers, and the evapotranspiration (ET) cover.

Capillary barriers work in concert with a cover layer of fine soil that supports the growth of plant roots. The purpose of the capillary barrier is to increase the water storage capacity of the fine soil layer. It is particularly advantageous where soils with high water-holding capacity are unavailable or too expensive. Experimental capillary barrier systems have sometimes failed when too much water accumulated above the barrier. The capillary barrier should be considered for use by the Air Force; however, application of this alternative will require careful selection of the design and construction team and should be viewed as an experimental cover.

Dry barriers—sometimes called convective air-dried barriers—are similar to the capillary barrier cover except that wind-driven, convective, or power-driven airflow through a layer of coarse material helps remove water that may infiltrate this layer. Dry barriers may be suitable for landfills in hot, arid climates; however, the literature does not address the limited water-holding capacity of the coarse layer or the required airflow rate to remove the water as it infiltrates the coarse layer. Although the dry barrier concept appears to hold promise, at present there is insufficient engineering design data to encourage its use except on an experimental basis.

Asphalt barriers can be used in place of compacted clay as a landfill component, and this modification could be useful for arid climate landfills where a clay barrier may fail because of soil desiccation. It should be noted that asphalt barriers are still experimental and do not appear suitable for widespread use on Air Force landfills.

Soil-plant covers are also called natural covers, earthen barriers, monofill covers, or monocovers. In arid and semi-arid regions where evaporation exceeds precipitation, these covers should be capable of preventing precipitation from reaching the waste by storing water in a soil cover until withdrawn by plants. However, most of the soil-plant landfill covers reported in the literature failed to prevent infiltration because of design or construction problems. Some were not designed with sufficient soil water-holding capacity to withstand a series of severe storms; some suffered from excessive compaction of the soil during construction, which was sufficient to limit or prevent adequate root growth.

Covers with modified surface runoff have proven successful in wet climates. Waterproof panels are placed between rows of vegetation to remove most or all precipitation from a substantial fraction of the landfill surface. This cover was successful in preventing deep percolation of water below the cover; however, it used a monoculture of plants, which reduced the reliability of performance. Both construction and long-term maintenance costs are high. It may be considered for experimental use.

ET covers use no barrier layer. They are specifically designed to provide adequate soil water-holding capacity and soil that supports rapid, robust root growth and water extraction. They differ from other innovative covers in two important ways: (1) they use natural systems without a barrier layer, and (2) the concept has been widely tested over long time periods in the field. ET cover design requirements overcome the deficiencies of “soil-plant” covers. Based on a preliminary analysis, it appears that application of the ET cover on currently unremediated Air Force landfills could result in potential savings of more than $500 million in landfill-cover construction cost.

1 Introduction

The advent of the environmental era during the 1960s in the United States brought with it a new appreciation for the adverse and chronic effects of solid waste disposal practices. Even the development of "sanitary" landfills decades earlier did nothing to protect the underground environment; instead, it primarily focused on disease prevention and aesthetic concerns. During this time, specific environmental objectives evolved that drastically changed the design concept for landfills, and a massive amount of legislation was enacted with the intention of preventing and mitigating pollution from landfill sites. As a result, today both the technical design of landfills and the applicable regulatory requirements are complex.

This document is one of a series that focuses on landfill covers. Other documents will (1) identify the current inventory of Air Force landfills, (2) provide a screening tool for the selection of landfill cover alternatives, (3) provide a field protocol for remedial investigations leading to landfill closure, and (4) evaluate computer models that may be useful for landfill cover design. The complete series will provide Air Force decision makers with fundamental information in the regulatory and technical concepts that drive landfill cover selection and design at Air Force installations and will also identify and define available alternatives.

1.1 Objectives

The Air Force is currently responsible for about 600 inactive landfills. There are thousands of landfills with similar needs within the purview of the Department of Defense (DOD). Because of the expense and risk associated with other methods of dealing with these wastes, they are usually contained in place. The primary action required to contain the waste in a landfill is the construction of a suitable cover (often called a final cover or a cap).

Although other options exist and are discussed in this report, for most of these landfills, the construction of a cover will likely be identified as the optimal remedial action. A primary objective of this report is to provide the Air Force with state-of-the-art information and references from the current literature on the selection, design, and construction of landfill covers. This information will help identify more cost-effective approaches and reduce remediation costs.

There are at least four important yet distinct incentives for the Air Force to obtain up-to-date information on the design and construction of landfill covers:

- Federal and state statutes mandate that each Air Force landfill must be identified for no further action, remediated, or removed.
- Each landfill creates a potential risk to human health and the environment.
- Designing and constructing an effective landfill cover is complex and requires a team of engineers and scientists with a broad knowledge base.
- Conventional landfill covers are expensive, and the Air Force needs more cost-effective alternative covers that meet remediation requirements.

Although landfill-cover design and construction has become a sophisticated operation, it is also very expensive. Typical costs for conventional covers on Air Force bases vary from $318,000 to $571,000 per acre (Hauser and Weand, 1998), so that expenditures in the tens of millions of dollars for a single landfill are not uncommon. These costs are associated with technologies selected as much to conform to regulations as to satisfy scientific and engineering requirements or environmental concerns. Within this decade, innovative approaches to landfill covers have been proposed and demonstrated. Under the appropriate circumstances, these approaches offer the promise of providing effective environmental solutions at lower cost. This report will explore the promise of these new technologies.

A Remedial Project Manager (RPM) facing a landfill remediation will need to understand the two principal, but distinct, determinants of a practical, cost-effective solution: regulatory requirements and technical approaches. This document reflects a review of recent technical literature and regulations and will provide the reader with a basic understanding of the following:

- The regulatory framework that establishes landfill cover requirements
- Regulatory latitude for the selection of innovative landfill covers
- The purposes of landfill covers and the common components of landfill cover systems
- The primary factors that influence the selection and design of a landfill cover at a particular site
- State-of-the-art landfill cover designs

Beyond this introduction, the report is organized into two major sections. Section 2 presents the regulatory framework that has controlled most of the landfill cover construction to date. As a practical matter, regulatory requirements are usually grounded in the Resource Conservation and Recovery Act (RCRA), but other pertinent federal legislation, directives, and policies are also discussed, and representative state regulations are reviewed. The report also discusses the approach required to gain regulatory acceptance of an innovative cover at a landfill site and the evaluation of landfill remediation options based upon risk and performance criteria.

Section 3 of this report provides the technical basis for landfill cover designs that will achieve environmental objectives. Various landfill cover designs are presented, and common landfill cover components are described. There is a clear commonality of purpose in these designs, in spite of their different technical principles. Innovative approaches that can offer acceptable environmental protection at lower cost under the appropriate circumstances are also illustrated.

A review of the recent literature concerning landfill covers—as well as a review of current regulations governing landfills—was required to compile the information in Sections 2 and 3. A topical bibliography, assembled as a result of this review, is included as a useful reference for those interested in acquiring a more detailed understanding of the various topics presented here. The bibliography is found in Appendix G of this report.

1.2 The Purpose of Landfill Covers

There are fundamental scientific and technical reasons for placing a cover on a landfill site. Although regulations appear to drive the selection and design of landfill covers today, these regulations originated from specific environmental concerns and have a technical basis. Landfill covers offer many environmental benefits, but there are three preeminent goals in their application:

- **Minimizing infiltration**: Water that percolates through the waste may dissolve contaminants and form leachate, which can pollute both soil and groundwater as it travels from the site.
- **Isolating wastes**: Exposed waste allows direct contact with potential receptors at the surface.
- **Controlling landfill gases**: The release of explosive or toxic gases can create a potential hazard in the vicinity of a landfill.

These three principal goals are common to all landfill cover designs and will be reiterated throughout this document. The way in which they are technically implemented can be quite different.

Landfill covers are inherently intended to remain in place and provide protection to the environment for an extended period, perhaps centuries. However, most commonly used cover technologies have only been in existence for about 20 years. It is not known exactly how landfill cover performance will change over time. Innovative covers that do not rely on an “impermeable” barrier may offer more reliability in this respect.

1.3 Characteristics of Air Force Landfills

The selection and design of a landfill cover is necessarily specific to a particular site. Site-specific factors are discussed in more detail in Section 3.1. However, Air Force landfills (and military landfills in general) have characteristics in common that set them apart from non-military landfills in operation today.

Over the years, military bases used landfills to dispose of solid wastes, including municipal waste, construction debris and rubble, industrial waste, cleaning solvents, paint strippers, and pesticides. The landfills at Air Force bases are usually trenches, pits, or other depressions in the earth into which waste has been deposited. While most commercial landfills are built with a complex liner system to collect leachate and prevent leakage into the underground environment, military landfills were generally constructed prior to the passage of RCRA and do not have a bottom liner. The Air Force shifted from landfilling to contract waste disposal during the late 1980s, so the majority of its landfills have been unused for many years. Much of the waste in these inactive landfills has already consolidated and decomposed, so that surface subsidence in the cover will probably be small. Landfill gas production can also be expected to be low, so gas control may not be necessary in the cover design; this factor could offer significant savings in cover costs.

The above characteristics should be kept in mind while reading the sections that follow. In particular, innovative landfill cover designs may have greater application at Air Force installations or other military sites than at landfill sites in general.

2 Regulations, Policies, and Processes

Federal and state regulations have long dictated not only the application of a landfill cover as a remedial alternative, but also its actual technical design. More recently, the Environmental Protection Agency (EPA) has adopted policies that are meant to speed remediation and encourage the use of innovative designs. This section provides a review of the regulatory and policy impacts on landfill cover implementation and design, as well as a discussion of how to use this information to gain acceptance for the use of an innovative cover at Air Force sites.

The key federal legislation governing the closure of landfills was written in the early 1980s, and remediation programs for the correction of past disposal practices followed shortly thereafter. Section 2.1—Federal Regulation Framework—briefly discusses the primary federal regulations governing landfill closure. RCRA is the controlling federal law for both municipal solid waste and hazardous waste landfills. For the most part, the remediation of old landfills is not addressed directly under RCRA, but it is regulated under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), with RCRA as the source of potential Applicable or Relevant and Appropriate Requirement (ARAR) standards for cleanup.

Landfills that are currently operating at Air Force bases are subject to their states' landfill regulations, and examples of state requirements are discussed in Section 2.2—State Regulation Framework. However, bases today have few operating landfills, so the closure of base landfills is generally conducted under the DOD's Environmental Restoration Program, following the CERCLA process, under which the RCRA and state regulations are considered as ARARs.

Given the prescriptive nature of both RCRA and many state regulations, the intimate association among CERCLA, RCRA, and state regulations has historically been an impediment to the selection and installation of alternative landfill covers. However, the same association may also be interpreted as providing latitude to install alternative covers under the CERCLA process because of the flexibility in selecting ARARs. EPA, DOD, and the states are fully aware of this dichotomy and have expended considerable effort in defining and supporting the role of innovative technologies in the nation's remediation programs. To lay the groundwork for understanding the regulatory flexibility, various resources for the development and application of innovative technologies, specifically alternative landfill covers, are discussed in Section 2.3—EPA Directives, Reports and Other Aids to Implement Innovative Technologies.

The process for guiding an Air Force RPM through this challenging regulatory environment toward the selection and implementation of an alternative cover is presented in Section 2.4—Latitude and Process for Alternative Technology—and in Section 2.5—General Approach for the Acceptance and Installation of an Innovative Cover.

Finally, a general concept for landfill closures is introduced in the Section 2.6—Risk-Based/Performance-Based Landfill Evaluation, which describes the technical basis for landfill closure. An Air Force RPM can use all the resources, regulatory latitude, and acceptance process discussed in this section to gain acceptance of sound closure criteria at their base.

Each Air Force base is in a unique regulatory environment. The specific state regulations, the exact relationship between the federal and state regulators, and the priorities and concerns of the public make each landfill closure decision a singular process rather than a routine regulatory exercise. Understanding this from the outset will allow the RPM to guide the process to a technically sound, protective, and cost-effective closure decision.

2.1 Federal Regulation Framework

RCRA is the controlling federal law for both municipal solid waste and hazardous waste landfills. RCRA enforcement authority is delegated to the states as each state adapts equal or more stringent regulations than those contained in federal rules and regulations. Most states' regulations closely follow the RCRA regulations. RCRA contains many specific requirements regarding the construction, operation, and closure of a landfill, including surface water requirements, a groundwater contamination detection monitoring program, a closure system assessment monitoring program, closure criteria, and post-closure care requirements.

The remediation of old landfills is generally addressed under CERCLA rather than RCRA, with RCRA considered as an ARAR. However, Air Force bases with active RCRA Permits are exceptions because landfill remediation is addressed as a "corrective action" as a part of the Permit requirement.

2.1.1 RCRA Landfill Closure Overview

RCRA divides landfills into two categories: landfills where hazardous wastes are disposed of in accordance with RCRA §264-Subtitle C Hazardous Wastes (HW); and landfills where only municipal wastes are disposed of in accordance with RCRA §258-Subtitle D Municipal Solid Waste (MSW).

At the time when RCRA was implemented, barrier-type covers using multiple low permeability layers were considered the most permanent and protective landfill cover options. While the regulations allow for some design flexibility, both municipal and hazardous waste covers have specific permeability requirements reflecting this prejudice. For covers of HW landfills, Subtitle C states a general performance requirement to minimize migration of liquids through the closed landfill, while §264.310(a)(5) imposes a permeability requirement—the final cover must have a permeability less than or equal to the bottom liner or natural subsoils. Landfills with Subtitle C covers (§264.310[b][1] and [2]) are also required to operate and maintain a leachate collection system and a leak detection system (see Appendix A).

For MSW landfills with Subtitle D covers, this same duality exists in the general goal of minimizing infiltration (§258.60[a]) and the specific requirement that the permeability of the final cover be less than or equal to the permeability of any bottom liner system or the natural subsoils, or in any case have a permeability no greater than 1×10^{-5} cm/sec (§258.60[a][1]) (see Appendix B). There is a specific option for alternative cover designs for Subtitle D landfills that allows the director of an *approved state* to allow an alternative final cover design that includes an infiltration layer that achieves an equivalent reduction in infiltration (§258.60[b][1]).

The goal of minimizing infiltration is readily achievable by alternative cover designs through processes other than reduced permeability layers (see Section 3.2.4). However, because these covers do not meet the specific permeability stipulations under RCRA, innovative covers are often rejected. In order to gain approval of alternative covers that control infiltration of water into the waste materials by processes other than controlling permeability, it will be necessary to review specific state regulations and to work with the regulators to determine available regulatory options.

In 1993, EPA introduced the concept of the corrective action management unit (CAMU)[1]. This modification of RCRA was intended to reduce or eliminate certain waste management requirements of the Subtitle C regulations that, when applied to remediation wastes, impeded the ability of EPA to select and implement reliable, protective, and cost-effective remedies. The practical effect of a CAMU is to allow consolidation of wastes from more than one landfill into one centralized landfill without triggering the RCRA rules regarding generation and disposal of HW.

Adoption of this rule by the states is varied. The CAMU concept is important for closure bases with multiple landfills, especially if some landfill locations impact intended land reuse options. If any of the fill components of these landfills are deemed to be HW, consolidation of these landfills would be precluded. However, by designating the landfills collectively as a CAMU, it is possible to consolidate the wastes into one landfill away from the reuse area. The design of the closure system for the consolidated landfill is only required to be protective of human health and the environment.

2.1.2 CERCLA Landfill Closure Overview

Most Air Force base cleanups are carried out under CERCLA (commonly referred to as Superfund) regardless of whether the site is on the National Priorities List (NPL). CERCLA establishes no specific cleanup standards or methods. Instead, CERCLA reaches out to all the other environmental, health, and/or facility siting regulations as ARARs. For landfill remediation projects, RCRA is the most significant source of ARARs. However, RCRA is intended to regulate the closure of operating landfills and is ill-suited to landfills that have received no waste for decades.

The implementation of alternative landfill covers depends on the ARAR determination for a particular site. If RCRA is found to be applicable to a cleanup, then the RCRA limitations and procedures discussed above must still be followed. Under RCRA, the appropriateness of Subtitle C requirements should be scrutinized closely at Air Force landfills containing only minor hazardous waste constituents. (The presence of hazardous waste constituents does not necessarily indicate that hazardous wastes were disposed of at a landfill.) The application of RCRA Subtitle C requirements by regulators makes the use of alternative covers difficult, even though in some cases these requirements are not justified.

[1] *Federal Register*, February 16, 1993, pp. 8658-8685.

The National Oil and Hazardous Substances Pollution Contingency Plan (NCP)[2] is the implementing rule for CERCLA and addresses selection of an alternative remedy in section 300.430(f)(1)(ii)(C), which states "*An alternative that does not meet an ARAR under federal environmental or state environmental or facility siting laws may be selected under the following circumstances: … (4) The alternative will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, or limitation through use of another method or approach*."

The NCP defines nine specific criteria for evaluation and selection of a remedy:

- Overall protection of human health and the environment
- Compliance with ARARs
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume through treatment
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community acceptance

All remedies are compared against these nine criteria to determine the best overall remedy selection. It may be difficult to show that innovative technologies meet criteria 2, 3, and 6. Regulatory, technical, and acceptance issues must all be addressed in selecting and implementing an alternative technology; therefore, it may be difficult to get final acceptance of innovative concepts. The ability of an Air Force RPM to gain consensus and final approval of an innovative landfill cover requires technical, regulatory, and community-relations expertise. The RPM and his team must be capable of laying the groundwork for an innovative technology and following the remedy selection process through its long and arduous path.

The extent of effort necessary to gain approval of an alternative cover at a particular landfill is discussed below in Section 2.4—Latitude and Process for Alternative Technology—and in Section 2.5—General Approach for the Acceptance and Installation of an Innovative Cover. An Air Force RPM is faced with significant and often conflicting urgency in selecting and implementing a remedy to meet the obligations of DOD guidance, Federal Facility Agreement schedules, and Base Closure deadlines. The opportunity to save significant costs—millions of dollars at a single site—may often be overtaken by such conflicting concerns.

2.2 State Regulation Framework

State regulations are important to the remediation of any site because they often are the controlling regulations. This report discusses specific federal EPA rules and regulations because they form the framework for all of the state regulations and because understanding EPA regulations provides a solid foundation for understanding regulations of individual states. Selected information is presented for both existing California and

[2] *Federal Register*, March 8, 1990, pages 8666-8865.

proposed Texas regulations that provide useful direction to Air Force personnel working in other states. The discussion of the proposed Texas regulatory framework is particularly interesting because Texas is proposing major changes that have the potential to make innovation somewhat easier in the future.

2.2.1 Proposed Texas Risk Reduction Program

Texas is in the final stages of an aggressive modification to its laws governing the remediation and closure of contaminated sites. It is expected that the new law—known as the Texas Risk Reduction Program (TRRP) rule—will be formally adopted in spring 1999. At the time this document is being written, the TRRP has been withdrawn for modification but will be re-proposed. The TRRP rule will establish a uniform set of risk-based, performance-oriented technical standards to guide response actions at affected properties. The adoption of this rule puts Texas at the national forefront of remedial environmental legislation. Appendix C contains excerpts from the original proposal of the Texas Natural Resource Conservation Commission (*Explanation of the Proposed Rule*) and the proposed language of *Subchapter D: Remedy Standards §§350.91-350.96*. The status of the rule and the modified version when it becomes available can be found on the Internet at: http://www.tnrcc.state.tx.us/waste/.

The TRRP rule, as originally proposed, will allow two levels of closure: Remedy Standard A and Remedy Standard B. *Remedy Standard A* will require removal or treatment of all contaminants in all media to achieve a risk-based cleanup standard without the use of any physical migration or exposure controls. *Remedy Standard B* will achieve the same level of protection, but contaminants will be allowed to remain at concentrations above the cleanup standard; the associated risks can be addressed by physical migration or exposure controls. The risk-based cleanup standards, or protective concentration limits, are established for each media by back-calculating from each pathway and receptor subject to acceptable risk-based exposure limits. Residential and industrial land uses are allowed for both standards.

The TRRP rule allows for a cost-effective remedy selection that addresses the risks at a particular site. The rule defines a "functioning cap" as a low permeability layer or other approved cover meeting its design specifications to minimize infiltration and migration of chemicals of concern and whose design requirements are routinely maintained. Alternative covers clearly meet these requirements. The final promulgation of the TRRP rule and the application of this common-sense, technically based remedial process promises to make significant improvements in cost-effective protection of human health and the environment.

2.2.2 California Landfill Closure Regulations

The California Integrated Waste Management Act and Solid Waste Disposal Regulatory Reform Act of 1993, section 40000 et seq. of the Public Resources Code (PRC), places the authority for waste management in the California Integrated Waste Management Board (CIWMB), State Water Resources Control Board (SWRCB) and the local enforcement agencies (LEAs). This act effectively integrated the functions of several agencies into the CIWMB and LEAs, with ancillary assistance from SWRCB and other appropriate state and regional agencies, as discussed below and in the regulations.

California law is based upon federal RCRA and other statutes, as are the laws in all of the other states. These laws generally are based on the barrier-type covers that constituted current technology when the federal rules were written; they are not reviewed here again. This discussion and the material included in Appendix D focus instead on rules for landfill covers and the opportunities offered by the California laws, rules, and regulations for use of innovative concepts in landfill covers.

The specific solid waste (SW) landfill cover requirements are found in California's Solid Waste Closure law [§21090 SWRCB—Closure and Post-Closure Maintenance Requirements for Solid Waste Landfills (C15: §2581 // T14: §17777, §17779)]. These requirements call for the installation of a "Low-Hydraulic-Conductivity Layer" compacted to attain a hydraulic conductivity of either $1x10^{-6}$ cm/sec (1 foot/year) or less, or equal to the hydraulic conductivity of any bottom-liner system or underlying natural geologic materials, whichever is less permeable, or another design that provides a correspondingly low through-flow rate throughout the post-closure maintenance period.

The SWRCB can allow any alternative final cover design that it finds will continue to isolate the waste in the unit from the effects of precipitation and irrigation waters at least as well as would a final cover built in accordance with applicable prescriptive standards. This so-called "low through-flow rate" is attainable by alternative cover designs, which are therefore permissible under the law.

Additional general closure flexibility is provided in SWRCB—General Requirements. (C15: §2510) 20080(4)(b). This regulation allows for alternative solutions to SWRCB regulations where the prescriptive remedy is infeasible and the alternative meets the requisite goals and performs an equivalent function to the prescriptive remedy. In order to prove infeasibility, the discharger must either show that there is an unreasonable burden and substantially greater cost than the alternative or that the prescriptive remedy will not meet the requisite goals of this regulation.

2.3 EPA Directives, Reports, and Other Aids to Implement Innovative Technologies

EPA, DOD, and the states support multiple programs, research efforts, and regulatory initiatives to develop and implement innovative technologies. EPA has developed guidance, policy, directives, and agreements on innovative technologies. A common theme throughout these efforts is to gain acceptance and approval for the implementation of innovative technologies and to overcome regulatory and technical conservatism. Resources available to RPMs support the use of innovative technologies, particularly alternative covers, and the following subsections provide RPMs a starting point for the selection of an alternative landfill cover at their site. Additionally, Appendix F provides a listing of Internet sites having up-to-date information on the application of innovative landfill technologies.

2.3.1 Promotion of Innovative Technologies in Waste Management Programs

EPA's Office of Solid Waste and Emergency Response (OSWER) Policy Directive 9380.0-25 defines EPA's support of innovative technologies, and it expresses

EPA's frustration with the difficulty of getting innovative technologies approved and implemented in the field. In the second paragraph of the Directive, EPA OSWER states: *"A recent analysis of Superfund Feasibility Studies found cases where innovative technologies were eliminated from consideration because they required testing to determine their applicability at a particular site. Promising new technologies should not be eliminated from consideration solely because of uncertainties in their performance and cost, particularly when a timely treatability study could resolve those uncertainties."*

In Directive Section (4)—Streamline RCRA Permits and Orders for Innovative Treatment Technology Development and Use—EPA writes, *"We need to work more as team members, rather than traditional regulators, to coordinate with EPA laboratories, other federal agencies, states and the private sector in pursuit of our common interest of furthering new processes."* The Directive continues in section (4)(a)—Avoid Unnecessary Regulatory Control—*"When considering new technology applications, we need to ask ourselves whether prior assurance that cleanup standards will be met is necessary. For treatability studies and demonstration projects, seeking assurance of success as a precondition to testing makes little sense since this is the purpose of the investigation itself."*

Directive Section (6)—Utilize Federal Facilities as Sites for Conducting Technology Development and Demonstrations—documents EPA's commitment to promote the use of federal facilities as demonstration and testing centers for innovative environmental technologies. *"Federal facilities offer unique opportunities for the development and application of both field site characterization and cleanup technologies. Regions are encouraged to work with states as co-regulators to ensure acceptance and with other federal agencies to promote testing and use of new approaches. Cooperative efforts are needed to develop permit conditions which do not unreasonably restrict technology demonstrations at federal facilities*."

Overall, this is a critical directive because it states EPA's explicit support for innovative technologies. However, EPA acknowledges that the regulatory environment at both the federal and state level is an ongoing impediment to the selection and implementation of innovative technologies. The Directive gives some helpful information to the RPM on how to build a consensus for a particular technology at their site.

2.3.2 EPA Policy for Innovative Environmental Technologies at Federal Facilities

EPA Administrator Carol Browner states in *EPA Policy for Innovative Environmental Technologies at Federal Facilities* (Figure 1) that *"EPA will … work with the Federal agencies and interested stakeholders to overcome the regulatory and institutional challenges affecting the application and commercialization of environmental technologies."* The Administrator thus provided very strong support for using innovative technologies at federal facilities. This directive should be distributed to participants at the start of any innovative technology discussion.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460
AUG 19 1994

THE ADMINISTRATOR

EPA Policy for Innovative Environmental Technologies at Federal Facilities

The Federal government has a responsibility to become a leader in promoting and developing technological solutions for environmental protection. Due to the magnitude of the Federal Facilities cleanup and compliance challenge and our commitment to catalyze technological solutions for environmental needs, Federal facilities offer unique opportunities for the development and application of innovative technologies and approaches to pollution prevention, source control, site investigation, and remediation.

Federal facilities offer unique opportunities for collaborative efforts on technology innovation involving EPA, other Federal departments and agencies, and the private sector. These opportunities have become even more apparent recently as the Departments of Defense and Energy shift missions and literally “open their doors” to allow both public and private groups to take advantage of their technological capabilities for environmental purposes.

Collaboration among the Federal government, states, the public, and industry to develop technological solutions to environmental problems will address environmental needs while creating jobs and spurring economic development. EPA will also work with the Federal agencies and interested stakeholders to overcome the regulatory and institutional challenges affecting the application and commercialization of environmental technologies.

EPA is committed to actively promoting and facilitating the use of federal facilities as demonstration and testing centers for the development of innovative environmental technologies. In addition, I encourage the incorporation of innovative technology conditions in appropriate EPA/Federal Agency clean-up and compliance agreements. Such technology conditions, when carefully crafted, can provide encouragement for innovation while still holding the Federal agency and regulators accountable for environmental protection.

Therefore, today I am announcing this policy to promote and support the use of Federal facilities as demonstration and test centers for the development and application of innovative environmental technologies.

To implement this policy, EPA shall:

Actively seek state, community and other stakeholder support and involvement in Agency policies that affect environmental technologies and in Federal facility technology development and demonstration projects;

Focus on private sector involvement to 1) enhance technology commercialization, job development, and economic growth; and 2) highlight real application and early field work for current clean-ups and the prevention of future pollution;

Seek opportunities to use innovative technology to reduce or eliminate waste or pollution;

Increase cooperative efforts with the federal and private sectors to determine how technology may factor into remedy selection;

Exercise leadership in the development of a coordinated interagency strategy implementing the concept of utilizing federal facilities as technology development and demonstration centers for pollution prevention, control and site investigation/clean-up; and

Provide direction by sponsoring informational and policy meetings on innovative technologies this year and in the future to serve as the basis for the development of this interagency strategy.

Through environmental improvement, economic growth and international export, EPA will continue to explore and define its interagency role in coordinating leadership, development and implementation of innovative environmental technologies. I encourage your strong support for this concept as it continues to evolve and take shape in the future.

Carol M. Browner

Figure 1. EPA’s Innovative Technology Policy

2.3.3 Application of the CERCLA Municipal Landfill Presumptive Remedy to Military Landfills

Presumptive remedies are preferred technologies for common categories of sites. They are based on historical patterns of remedy selection and the EPA's scientific and engineering evaluation of performance data on selected technologies. By streamlining site investigation and accelerating the remedy selection process, presumptive remedies are expected to ensure the consistent selection of remedial actions and reduce the cost and time required to clean up similar sites. Presumptive remedies are expected to be used at all appropriate sites. Site-specific circumstances dictate whether a presumptive remedy is appropriate at a given site.

Presumptive remedies employ a streamlined risk assessment. A streamlined risk assessment for a municipal landfill focuses on the most obvious problems at the landfill (e.g., groundwater contamination, leachate, landfill contents, and landfill gases) to provide a clear and quick indication that remedial action is warranted at the landfill. The risk assessment is streamlined because it does not provide a fully developed, quantitative assessment of the risks associated with all contaminants, exposure pathways, and potentially exposed receptors. The streamlined risk assessment (1) identifies exposure pathways in a conceptual site model, (2) explains how the presumptive remedy addresses each pathway, and (3) focuses on risk assessment for any pathways not addressed by the presumptive remedy.

EPA established source containment as the presumptive remedy for municipal landfill sites in the *Presumptive Remedy for CERCLA Municipal Landfill Sites.* The municipal landfill presumptive remedy should also be applied to all appropriate military landfills using the guidance in *Application of the CERCLA Municipal Landfill Presumptive Remedy to Military Landfills.* This directive provides a step-by-step approach for determining when a specific military landfill is an appropriate site for application of the containment presumptive remedy. It identifies the characteristics of municipal landfills that are relevant to the applicability of the presumptive remedy, addresses characteristics specific to military landfills, outlines an approach for determining whether the presumptive remedy applies to a given military landfill, and discusses administrative record documentation requirements. Appendix E illustrates EPA's presumptive remedy selection procedure for landfill closures at military landfills.

2.3.4 Joint EPA/State Agreement to Pursue Regulatory Innovation

This agreement[3] was prepared jointly by the EPA and Environmental Council of the States to promote and implement future regulatory innovation efforts. The agreement encourages and facilitates the exploration of ideas that are potentially more cost-effective or have a better environmental impact. The following is an excerpt from the agreement:

[3] U. S. Environmental Protection Agency, Office of Reinvention, Joint EPA/State Agreement to Pursue Regulatory Innovation, *Federal Register*, May 5, 1998, pp. 24784-24796.

States and EPA agree that the following principles should guide us as we develop, test and implement regulatory innovations:

Experimentation: Innovation involves change, new ideas, experimentation and some risk of failure. Experiments that will help us achieve environmental goals in better ways are worth pursuing when success is clearly defined, costs are reasonable, and environmental and public health protections are maintained.

Environmental Performance: Innovations must seek more efficient and/or effective ways to achieve our environmental and programmatic goals, with the objective of achieving a cleaner, healthier environment and promoting sustainable ecosystems.

Smarter Approaches: To reinvent environmental regulation, regulators should seek creative ways to remedy environmental problems and improve the environmental protection system, and be receptive to innovative, common sense approaches.

Stakeholder Involvement: Effective stakeholder involvement produces better innovation projects and catalyzes public support for new approaches. Stakeholders must have an opportunity for meaningful involvement in the design and evaluation of innovations. Stakeholders may include other state/local government agencies, the regulated community, citizen organizations, environmental groups, and individual members of the public. Stakeholder involvement should be appropriate to the type and complexity of the innovation proposal.

Measuring and Verifying Results: Innovations must be based on agreed-upon goals and objectives with results that can be reliably measured in order to enable regulators and stakeholders to monitor progress, analyze results, and respond appropriately.

Accountability/Enforcement: For innovations that can be implemented within the current regulatory framework, current systems of accountability and mechanisms of enforcement remain in place. For innovations that involve some degree of regulatory flexibility, innovators must be accountable to the public, both for alternative regulatory requirements that replace existing regulations and for meeting commitments that go beyond compliance with current requirements. Regulators will reserve full authority to enforce alternative regulatory requirements to ensure that public health and environmental protections are maintained, and must be willing to explore new approaches to ensure accountability for beyond-compliance commitments.

State-EPA Partnership: The States and EPA will promote innovations at all levels to increase the efficiency and effectiveness of environmental programs. We must work together in the design, testing, evaluation and implementation of innovative ideas and programs, utilizing each other's strengths to full advantage.

EPA agrees to establish a process that ensures timely review and decision-making on State innovation proposals based on implementation of the above seven principles. The States agree to consult early with EPA, to develop proposals consistent with the above principles, and to involve stakeholders. EPA and the States agree on the need for a clearinghouse of regulatory innovations so that promising ideas can be shared across state lines and within EPA.

This agreement powerfully reinforces the commitment by the EPA and the states to find innovative regulatory solutions and to avoid being constrained by outdated or overly restrictive regulations. It is important that the agreement emphasizes that regulatory innovation activity should start with the states because the states are generally delegated RCRA authority and they need to support and pursue regulatory relief.

2.3.5 The Federal Remediation Technologies Roundtable

The Federal Remediation Technologies Roundtable was established in 1990 as an interagency committee to exchange information and to provide a forum for joint action regarding the development and demonstration of innovative technologies for hazardous waste remediation. Roundtable member agencies expect to complete many site remediation projects in the near future, and recognize the importance of providing expedited access to federal resources for technology developers and others interested in innovative technology development. The following is a list that the Roundtable compiled of active federal government programs promoting the development and implementation of innovative technologies.

Federal Site Remediation Technology Development Assistance Programs

Interagency R&D Assistance Programs

- National Environmental Technology Test Sites Program (NETTS)
- Rapid Commercialization Initiative (RCI)
- Remediation Technologies Development Forum (RTDF)
- Small Business Innovative Research Program (SBIR)
- Strategic Environmental Research and Development Program (SERDP)

U.S. Department of Defense R&D Assistance Programs

- Air Force Center for Environmental Excellence/Innovative Technology Program
- Environmental Security Technology Certification Program (ESTCP)
- Naval Environmental Leadership Program (NELP)

U.S. Department of Energy R&D Assistance Programs

- Industry and University Programs Area
- Program Research & Development Announcements (PRDAs)
- Research Opportunity Announcements (ROAs)
- Small Business Technology Transfer Pilot Program

U.S. Environmental Protection Agency R&D Assistance Programs

- Environmental Technology Initiative (ETI)
- Environmental Technology Verification Program (ETV)
- National Center for Environmental Research and Quality Assurance (NCERQA)
- Superfund Innovative Technology Evaluation Program (SITE)

EPA analyzed market trends for innovative technologies and determined that at least 30 percent of the Superfund sites will implement innovative technologies for some degree of source control. Alternative landfill covers should be a significant part of the innovative technology used.

The number of federal government programs involved in the development of innovative technologies is impressive. Each of these programs has identified target technology gaps for the sites within their agency's responsibility. Bringing these technologies through development, testing, and acceptance is a challenge faced by each agency. DOD's Environmental Security Technology Certification Program summarizes the challenge in their statement, "*Successful demonstration facilitates the acceptance of innovative technologies by users and the regulatory community*."

2.4 Latitude and Process for Alternative Technology

Selection of innovative technologies for use at sites in the CERCLA and RCRA cleanup programs is difficult because there is an inherent conflict between stringent regulatory interpretation of cleanup requirements and the application of innovative technologies. EPA is aware of this conflict and has attempted to provide its regulators with significant support in the selection and application of innovative technologies. The development and application of innovative technologies has been identified as the weak link in the remediation process since the earliest days of the CERCLA and RCRA cleanup programs. Congress acknowledged this issue in the Superfund Amendments and Reauthorization Act of 1986 (SARA)[4]: "*The Administrator is authorized and directed to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies … which may be utilized in response actions to achieve more permanent protection of human health and welfare and the environment*."

Twenty years into this nation's remedial programs, innovative technologies offer significant promise of reducing the huge cost burden of remediation. The greatest strides in these cost savings technologies are being made in the use of biological processes to control migration or treat various wastes. Particularly important are *in situ* technologies—biological, physical, and chemical processes. For example, the underground petroleum cleanup program costs were reduced by billions of dollars with the successful understanding and implementation of bioventing and monitored natural attenuation; the Air Force was a compelling force in the development and acceptance of these technologies. The development and use of other biological systems is expanding to the treatment of air, wastewater, soil, sediments, groundwater, landfill covers, and the waste material itself. The battle for implementing these technologies continues to be waged at individual sites.

EPA has laid extensive groundwork in the application of innovative technologies. The challenge comes with the approval and fielding of a particular technology at a specific site. Approval of innovative landfill covers is often presented as the following five-step approach (Burnley, 1997):

1. Review all available data to determine the appropriateness of an alternative cover.
2. Meet with regulating agency to identify concerns, and judge feasibility.
3. Develop potential alternative designs and cost estimates and compare results.
4. Laboratory test and computer model proposed designs.
5. Prepare report.

[4] Public Law 96-510.

This process is applicable at landfills that are completing operation and are ready to undergo closure. However, at federal facilities, there are few landfills at which a simple straight-through innovative technology acceptance process is possible. In general, Air Force landfills have been unused for years or decades, and these landfills have been studied through various remedial investigations and feasibility studies. Often landfill closure schedules are included in CERCLA Federal Facility Agreements or RCRA Permits. The relationship of a particular Air Force base and its state and federal regulators and the public is based on nearly two decades of remedial programs. The introduction and acceptance of an alternative closure at one landfill is not a singular matter; instead, it must be seen in the context of the current base remediation program.

The selection and approval of an alternative cover at a particular landfill at an Air Force base is a lengthy process. Each of the sequential steps described above must be addressed, but some issues must be dealt with concurrently and/or iteratively. Approval of an alternative landfill cover may require additional monitoring and stipulations (e.g., the discovery of increased groundwater contamination or other releases may require the installation of a conventional cover). The Air Force RPM should coordinate input from various Air Force experts in their command, from their service center, and from contractors. They must then develop a unified presentation of the particulars of a proposed technology and provide reasons for application of this technology at a particular site. The technology must be shown to meet the performance requirements of a landfill cover; the benefits to the Air Force may include cost advantages, schedule improvement, or greater risk reduction.

Alternative landfill cover technology may require relief from some regulations or ARARs. Some RCRA regulations are so specific that the performance requirement of a final cover is focused on the permeability of specific layers. Yet innovative landfill covers may use different mechanisms to control water movement. Innovative covers should meet the performance requirements for the cover; however, they may not be strictly equivalent to conventional covers because they contain no “impermeable” layers. Equivalency between alternative and conventional covers may imply that a non-barrier is equal to a barrier cover, which is not possible. However, equivalency of performance requirements between conventional and innovative technology is not only possible, but also an understandable specification for acceptance.

The RTDF Phytoremediation of Organics Action Team, Alternative Cover Subgroup—an EPA-sponsored forum with participation from EPA, states, universities, Air Force, and industry—is a major proponent of innovative or alternative landfill-cover technologies. The group has identified several key issues related to the acceptance of alternative covers. The following is abstracted from various discussions and meetings of the RTDF and posted on their web page (www.rtdf.org). None of the following information reflects the Air Force’s, EPA’s, or any other member organizations’ formal stand on a particular issue. Key issues identified by the Forum related to the acceptance of alternative covers include the following:

- **Public Acceptance:** Public perception of protectiveness is dependent on many factors. The specific technical arguments are often not well communicated and the perceived emphasis on cost savings can create doubt regarding protection of public health.

- **Regulatory Impediments:** Permit writers need to be assured that the alternative cover provides the same level of protection and risk reduction as a traditional cover. Regulatory acceptance of alternatives will be based on technical demonstration and evaluation.
- **Equivalency/Performance:** Current RCRA design guidance is based on the hydraulic permeability of specific layers in the final cover. Alternative covers generally control water movement through other mechanisms. Long-term performance and maintenance requirements are also important performance issues that must be addressed and demonstrated. The issue of equivalency and long-term performance may ultimately require formal regulatory relief to ensure widespread acceptance and ultimately to allow proven alternative covers to assume their role as accepted alternatives.
- **Risk Issues:** Human health and environmental. The driving force of all landfill covers is the protection of human health and the environment. Alternative covers must provide protection that is comparable to conventional covers in controlling the source, migration and exposure to contaminants.
- **Modeling:** The long accepted standard model for landfill cover performance is the Hydrologic Evaluation of Landfill Performance (HELP) model. HELP was not developed to consider the full complexities of climate, plant growth, and evapotranspiration (ET). There are other models that handle each of these factors with greater sophistication; however, there is neither widespread familiarity nor acceptance of these models among the regulators.
- **Design Guidance:** The design of alternative covers has to date been an isolated activity directed at specific sites. There is no general design guidance available for alternative covers. This lack of generally accepted design criteria is a time consuming impediment in every approval attempt.
- **Monitoring Methods:** Alternative covers may be subjected to additional monitoring requirements to determine specific performance variables. The gathering of this performance data is crucial to the proof of the particular alternative cover concept, as well as calibrating models and developing general design criteria. These requirements may initially increase costs until the design has been proven, but for landfills closed at a later date, costs could be much less.

2.5 General Approach for the Acceptance and Installation of an Innovative Cover

The selection of an innovative cover at a single landfill can result in performance equal to a conventional cover, yet may save millions of dollars (see Section 3.2 of this report for a discussion of innovative landfill covers). The knowledge base and choices of alternative covers are expanding rapidly; therefore, previously chosen cover remedies for a landfill undergoing closure should be reexamined to determine if an alternative cover is appropriate. The earlier in the process of remedy selection that changes are made, the easier it will be to address the technical, regulatory, and acceptance issues. However, CERCLA[5] permits modification of a Record of Decision (ROD) at any time before the completion of the Remedial Design.

The following 11-step process is applicable to the closure of all Air Force landfills. The process described may be iterative, and each step may have significantly different emphasis at a particular base or for a particular landfill.

1. Determine risks at the specific landfill.
2. Determine performance requirements to address identified risks.
3. Select alternative technology and gather technical performance data, modeling and field demonstration studies.
4. Present a unified Air Force proposal to the regulators for use of an alternative cover.
5. Seek wide regulatory participation, including regulatory managers, EPA headquarters and laboratories, and State technical offices.
6. Aggressively challenge regulatory interpretation of ARARs or other rules that limit alternative cover selection and use.
7. Present the proposed technology to the Remedial Action Board and the public, preferably with regulatory buy-in.
8. Complete any required modeling, design criteria, and/or feasibility testing.
9. Formally select the alternative cover in the decision document (i.e., ROD).
10. Complete the design and monitoring plan.
11. Construct an alternative cover and gather monitoring and performance data. Disseminate the information within the Air Force to build support and acceptance of alternative covers.

The increased protectiveness and potential cost savings offered by appropriate alternative covers demands that each Air Force RPM review these options for each closing landfill. The successful demonstration of alternative covers at Air Force landfills will ultimately translate into savings of hundreds of millions of dollars to taxpayers and the private sector (Hauser and Weand, 1998).

2.6 Risk-Based/Performance-Based Landfill Evaluation

The preceding discussions of regulations and the selection of appropriate landfill cover options illustrates the limits imposed on making purely “technical” decisions to select new technologies and remedial options. Risk-Based/Performance-Based (RB/PB) landfill evaluation introduces a process that eliminates regulatory prejudices for a particular technology. There is already a strong regulatory basis for this process in the NCP and in the proposed TRRP rule, however the successful use of the process discussed here has been limited. Air Force RPMs can use the resources identified in Sections 2.1 through 2.5 of this report to successfully follow this approach in their landfill closure decisions.

[5] The National Oil and Hazardous Substances Pollution Contingency Plan (NCP), *Federal Register*, March 8, 1990, pages 8666-8865, § 300.435(c)(2)(i) and (ii)

An RB/PB landfill evaluation is a technically based approach to select protective remedial options based on the specific conditions at a landfill. Using RB/PB evaluation will allow the landfill owner to determine the specific technical performance requirements necessary to address all risks at a landfill. After these technical performance requirements are determined and accepted by the public and regulatory community, any particular landfill remediation scenario that meets them—including alternative or innovative covers—can be selected.

The RB/PB landfill evaluation process follows four well-defined steps used in environmental risk assessments:

1. **Identification of Releases**: Based on known waste materials and environmental sampling, determine the releases associated with a particular landfill, including the following:
   - Surface materials
   - Gas generation
   - Leachate production
   - Groundwater contamination
2. **Exposure Assessment**: Determine the exposure pathways to potential receptors, including the following:
   - Direct contact
   - Airborne contamination
   - Surface water or groundwater contamination
3. **Risk Assessment**: Determine the risks associated with each source–pathway–receptor combination.
4. **Performance Requirements**: Determine the specific performance requirements of each action that must be taken to address the risks identified, including the following:
   - Cover requirements to eliminate direct contact
   - Limitation of infiltration to control leachate generation
   - Collection and/or treatment of gas, if necessary
   - Control of groundwater contamination
   - No-further-action if no significant risks were identified

After a performance requirement has been established for a particular remedial action, any remedial alternative meeting that requirement can be selected and applied at that landfill. This process eliminates the need to follow the classical ARARs approach to determine closure requirements and allows the owner to select the most technically sound and cost-effective alternative to address the risk at a particular landfill.

3 Landfill Cover Technology

Final landfill covers (sometimes called caps) are the focus of this discussion; they are placed during remediation and remain in place as an essential part of the waste containment system. The use of the word “cover” in this section will be understood to refer to a final landfill cover. Over the past several decades, technologies have developed and advanced to enable the effective covering of landfills in accordance with environmental goals. At the same time, the process has become an expensive proposition and one largely driven by regulation. Ironically, regulations are sometimes blindly followed to the neglect of innovative technologies that can provide an environmentally responsible solution at considerable cost savings.

This section offers a review of the types of landfill covers that are available today and identifies the important factors that must be considered in selecting and designing them. Section 3.1 discusses the site characteristics that play a dominant role in selecting an appropriate landfill cover. Section 3.2 describes various technical approaches for achieving the aims of a landfill cover, including conventional barrier methods and an innovative approach that eschews physical barriers. Section 3.3 provides a detailed look at specific elements that are important to the design process and how these elements are handled in practice. Finally, Section 3.4 furnishes lessons learned from experiences in landfill cover failures and experimental work.

3.1 Site-Specific Aspects of Landfill Cover Selection and Design

Whereas the purposes of a landfill cover (see Section 1.2) are clear, the particular implementation as translated into design elements is dependent on specific site characteristics. The site characteristics that have a dominant influence on choosing an appropriate final cover include climate, soils, landfill characteristics, hydrogeology, gas production, seismic environment, and reuse of landfill areas. Each of these factors is discussed below.

3.1.1 Climate

Precipitation (rain, snow, and sleet), solar radiation, temperature, and wind are the main climatic factors that affect landfill covers. Precipitation amount and intensity, of course, have a direct bearing on infiltration of water into the cover and, potentially, into the buried waste. Climatic factors also strongly influence evapotranspiration, which acts to reduce infiltration into the waste. Degradation rates of biodegradable wastes will be affected by climatic variables through effects on moisture content and temperature. Soil erosion is directly affected by rainfall intensity and wind.

It is important to note that the commonly reported annual precipitation amounts do not provide sufficient information by which to evaluate a site. Seasonal and daily variations are important considerations. For example, if precipitation is seasonally distributed such that the majority falls during the period when vegetation is dormant, the potential for infiltration is much greater than if the precipitation falls mainly during periods of active growth. In some areas of the United States, snowpack accumulates during the winter months and then melts during a relatively short period in the spring. At this time, ET may be low and the ground not thawed; both circumstances will impact infiltration rates.

Beyond macro-climatic effects, there is also a strong influence of daily or even hourly patterns. A series of precipitation events that saturate the soil will lead to greater infiltration than the same total amount of precipitation spread over a longer time period. The antecedent moisture condition is just one factor that illustrates the complexity of climatic interactions that have to be considered in evaluating potential landfill covers. In addition to the general conditions, the concept of a "critical event"—one which produces extreme conditions—has to be taken into account. An example of such a critical event would be an extended period of rain following snowmelt that coincides with a period when vegetation is dormant and may occur only rarely.

3.1.2 Soils

The availability of appropriate local soils is an important consideration in any landfill design, as it is often needed for the surface layer, as well as for a compacted barrier layer. Major factors determining effectiveness of the soil for supporting vegetation are grain size, soil pH, and cation exchange capacity. An adequate supply of nutrients to support vigorous plant growth is also required but can be achieved by using soil amendments.

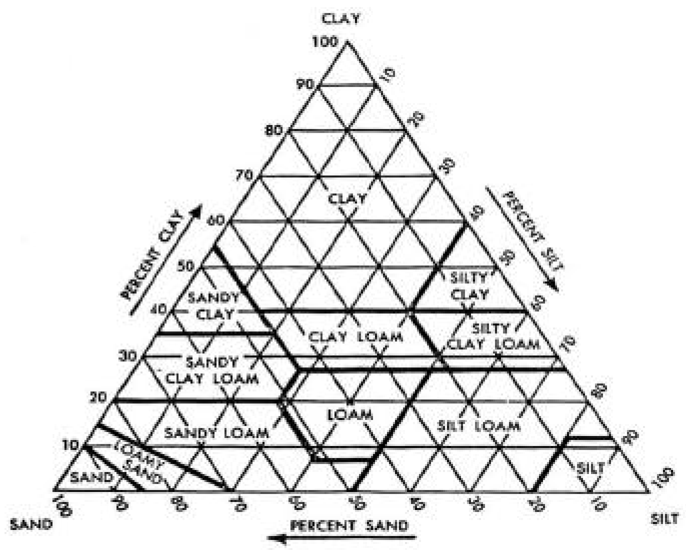

Figure 2. USDA Textural Classification of Soils

The U.S. Department of Agriculture (USDA) soil textural classification guide is shown in Figure 2. Although soil can be classified by visual inspection, the determination of soil type and soil properties should be based on appropriate soil testing. Soils should be classified and described for each site by a professional soil scientist or soil classifier. Generally, loam soils provide excellent cover for landfills. Soils made up largely of sand tend to dry out rapidly because they have low water-holding capacity and they lose nutrients by leaching. Differences in soil type also influence the selections of vegetation and mulch.

A landfill cover that relies on a conventional barrier system often incorporates a compacted clay layer (CCL) into the design. The availability of local soil that has the necessary properties to compose this layer is a critical cost factor in selecting the appropriate design.

Accurate information about soils on and near a site is particularly valuable for the evaluation of alternative covers. The design of ET covers, for example, is heavily dependent upon the specific characteristics of soils used. Water-holding capacity, in particular, is important, and the cover will not be practical unless sufficient soils with the appropriate characteristics are available near the site.

3.1.3 Landfill Characteristics

Some of the characteristics that affect cover design include the type of waste deposited, whether or not the landfill has a liner, the age of the landfill, whether the landfill is active or inactive, and whether or not leachate is being produced.

The type of wastes disposed in a landfill leads to its classification as municipal or sanitary (having basically household wastes), hazardous, radioactive, or mixed waste. The waste classification directly impacts the cover design because of both the technical and the regulatory requirements. For example, radioactive waste requires long-term storage and must consider the potential generation of radon gas. Air Force landfills hold primarily municipal type wastes, but many have received waste solvents, fuels, or other hazardous materials. The physical form of the waste and its chemical properties are an important consideration in selecting materials for the cover. If the buried waste is biodegradable, production of landfill gas can be anticipated and gas collection must be considered when designing the cover.

A bottom-liner system, which is required for any landfill constructed today, is a complex landfill component, and any final cover design must consider its specific properties, if present. However, almost all Air Force landfills were built before the advent of modern rules and regulations. A recent survey indicated that only 1 of 229 U.S. Air Force landfills surveyed had a bottom liner (Hauser and Weand, 1998). Therefore, cover system design for the remediation of Air Force landfills should typically not be restricted by rules and regulations that are pertinent to modern RCRA landfills with liners.

As a landfill ages, the degradation of the waste and the pressure of overlying materials leads to settling of the waste, sometimes by as much as 33 percent (Suter et al., 1993). The resulting subsidence of the overlying cover can cause severe problems, including separation of geomembranes (GMs), development of cracks in clay barriers, and slope changes that adversely affect water flow and retention. Although gas production in a landfill can continue for long periods, high rates occur over relatively short periods—perhaps up to ten years. Hauser and Weand (1998) found that 79 percent of Air Force landfills have been dormant for more than 20 years. Therefore, in comparison to a modern landfill that was covered immediately after filling, the final cover design for an Air Force landfill is less likely to require the expense of a gas collection system and less likely to sustain surface subsidence that adversely impacts the finished cover.

3.1.4 Hydrogeology

The distance between the bottom of an unlined landfill and the water table is an important determinant of the probability that groundwater has been or may be contaminated. If the landfill has no liner but rests on highly impermeable bedrock, shale, or clay, and if the depth to groundwater is great, then an old Air Force landfill poses little threat to groundwater. Therefore, the geology of the site (especially the lithology between the waste and permanent groundwater) is an important consideration. If waste is actually in contact with groundwater, a cover alone cannot provide a complete remedial solution for the site. A landfill cover at such a site should be selected with extra care and integrated with other remediation technologies being employed.

3.1.5 Gas Production

Gas production must be considered in the overall cover design. Natural decay of wastes and volatilization of wastes in landfills may produce sufficient toxic and/or explosive landfill gas to warrant gas control systems under the cover. Gas control systems may be either passive (natural flow) or active (using pumps). A cover that employs a conventional barrier layer is likely to require an expensive gas control system because the barrier is likely to trap gas produced at even low rates to yield dangerous volumes of explosive and/or poisonous gas. Some innovative covers, such as the ET cover, contain no barriers and may allow small amounts of landfill gas to pass harmlessly into the atmosphere.

3.1.6 Seismic Environment

Earthquakes are a significant threat to public safety and welfare over many parts of the United States, particularly the West Coast, Alaska, parts of the Rocky Mountains and the Mississippi Valley, and selected areas of the Eastern Seaboard. The ground-shaking associated with earthquake activity can damage landfill infrastructure in many ways, including landslides on the cover, rupture of barrier layers, breakage of conduit lines (e.g., gas control and drainage systems, electrical controls), and changes in drainage slopes. Within seismic hazard zones, landfill designs should be evaluated using site-specific seismic risk assessment criteria. Richardson and Kavazanjian (1995) have written an extensive treatment of this aspect of landfill design.

3.1.7 Reuse of Landfill Areas

Land reuse is an important consideration in landfill cover selection and design. The very fact that human activity is expected—and even encouraged—on a final landfill cover requires that more critical attention be given to its design. Former landfill sites find new life as parks, golf courses, nature areas, and bicycle paths. The anticipated use will require using compatible materials in the cover, perhaps modifying the topography, and selecting vegetation that not only provides the necessary cover functions but is also appropriate for the end use. Some apparently beneficial uses may be in conflict with primary cover purposes. For example, golf courses are usually irrigated frequently, which can result in large volumes of water moving below the root zone and potentially into the waste. Golf courses on landfill covers pose immediate problems because one of the principal objectives of a landfill cover—to minimize infiltration—probably cannot be achieved.

3.2 Landfill Covers and Their Components

Landfill covers are used at various times during a site's active life. At modern landfills, a thin cover is placed over the waste at the end of each day to control odors, prevent litter movement by wind, and keep rodents, birds, and insects out of the waste. Areas of an active landfill that will not be covered with additional waste or a final cover for an extended time are often protected by intermediate covers. Intermediate covers provide the same function as daily cover and also encourage surface runoff. McBean et al. (1995) present a more complete discussion of daily and intermediate landfill covers. Landfill covers placed during remediation—sometimes referred to as final covers or caps—are the focus of this discussion; they remain in place as an essential part of the waste containment system.

Landfill covers function as a protective layer to isolate the underlying waste from the environment; for many landfills, this layer is the most important component of the waste containment system. The requirements for cover performance are different for different types of waste. For example, an important requirement for a cover over a landfill containing significant quantities of radioactive materials is control of even small quantities of radioactive gases. In contrast, a military landfill that has been inactive for more than 20 years and contains municipal waste may not require any gas control system within the cover.

This discussion focuses on landfill covers for military landfills, which have distinctive characteristics affecting cover selection and design (see Section 1.3). For example, they usually have no bottom liner, have been unused for many years, and contain primarily municipal-type wastes. As stated earlier in this report (Section 1.2), there are three primary environmental goals for landfill covers:

- Minimizing infiltration of precipitation into the waste
- Preventing contact between receptors and the waste
- Controlling landfill gases

The landfill cover must minimize infiltration of precipitation because water that percolates through the waste may carry soluble wastes downward to groundwater, thus creating a threat to human health or the environment. An effective landfill cover can control this threat to groundwater. Covers that meet the infiltration requirement will usually satisfy the requirement that the waste should be isolated from receptors. Depending upon the site conditions, the cover may also be required to control gas produced by the landfill and to keep some types of barrier layers within the cover from freezing.

Because a landfill cover will likely remain in place for decades or even centuries, there are many design considerations that are important to maintain its functions and ensure long cover life. Specific design elements—including erosion control and slope stability—are discussed in detail in Section 3.3.

Engineered landfill covers have been employed only in the last few decades. Nearly all landfill covers in place today are conventional, barrier-type landfill covers. Compacted clay and synthetic materials are common components in these barrier-type covers. These designs, which are often accepted as presumptive remedies, place a barrier layer within the cover that is intended to prevent water from moving downward in response to the force of gravity. In effect, these covers are designed to oppose the forces of nature. Some innovative cover systems also rely upon the barrier concept, but others do not. Later sections discuss innovative covers and their use of the barrier concept.

3.2.1 Conventional Landfill Covers

Conventional covers employ barrier technology and typically include five layers above the waste (Figure 3); some covers employ only some of these layers. The top layer consists of cover soil that is typically 24 inches thick and supports a grass cover that provides wind and water erosion control. The second layer is a drainage layer that quickly removes any water that percolates through the cover soil; the water is stopped by the underlying barrier layer. The barrier layer consists of either a single low-permeability barrier or two or more barriers in combination. The fourth layer is the gas control layer that is needed under the barrier to remove landfill gases before they can accumulate in harmful amounts. The bottom layer is of variable thickness and material, and provides a foundation for cover construction. It separates the waste from the cover and establishes sufficient gradient to promote rapid and complete surface drainage from the finished cover.

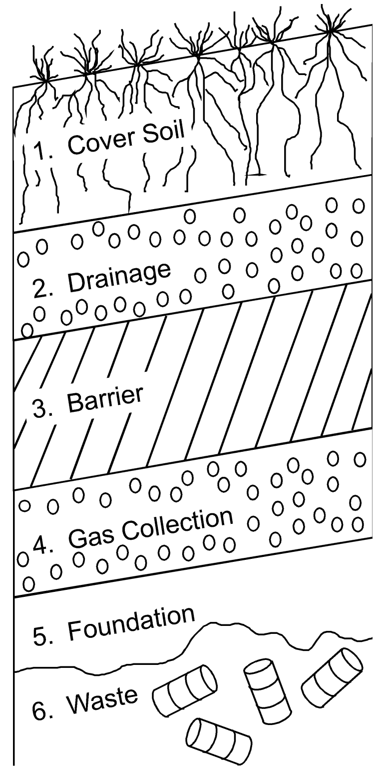

Figure 3. Typical Components of a Conventional Barrier-Type Landfill Cover

There are many different configurations of conventional barrier-type landfill covers. As discussed in Section 3.1, the type of waste, climate, and other variables require different components in the cover. Table 1 describes some of the functions and materials used in conventional barrier-type landfill covers. These components are discussed in more detail in the following sections.

Table 1. Components of Conventional, Barrier-Type Landfill Covers

Layer	Primary Function	Typical Composition
Cover Soil	• Control water and wind erosion • Support vegetation • Store water • Protect from freeze-thaw cycles	• Topsoil • Gravel or cobbles
Drainage	• Quickly remove infiltrating water • Protect barrier layer from freeze-thaw damage • Maintain stability	• Sand and/or gravel • Geonets • Geocomposites
Barrier	• Stop downward flow of water • Control gas flow from the waste	• Compacted clay • Geomembranes • Geosynthetic clay layers • Geocomposites
Gas Collection	• Transmit gas to collection points for removal	• Sand and/or gravel • Geosynthetics
Foundation	• Separate cover from waste • Provide correct land surface slope	• Soil • Geotextile filters

At present, conventional barrier-type covers represent the predominant final landfill-cover technology. Although there are many variations in specific design details, some or all of the functional layers described above can be found in nearly all existing landfill covers. Other components may be added to the functional layers described above to meet the specific requirements at a site. For example, gravel may be added to the surface soil in desert regions to control wind erosion, or animal intrusion layers of cobbles or other material may be added to protect hazardous radioactive waste sites. A more complete discussion of conventional covers may be found in Koerner and Daniel (1997), McBean et al. (1995), Kreith (1994), and Tchobanoglous et al. (1993).

3.2.1.1 The Cover Soil Layer

The primary function of the surface layer is to control wind and water erosion by supporting an adequate vegetative cover. The soil should have adequate physical properties to store sufficient water for plant use, and chemical properties to provide the necessary nutrients for plant growth. Fertilizers or other soil amendments may be required to establish a good surface layer. Selecting an appropriate vegetative species is essential for the proper functioning of the surface layer. Grasses should be indigenous to the area, hardy, and drought-resistant. This is important not only for aesthetic reasons, but also to ensure that surface erosion is controlled.

The cover soil layer is usually about 24 inches thick. The thickness of soil cover needed depends on the climate, soil properties, and vegetation type. A protection layer is sometimes installed under the soil used for vegetation support, as part of the cover soil layer to add protection against freezing of the barrier layer or for other reasons. The surface slope should be at least 2.5 percent to ensure adequate surface drainage after landfill settlement. Steep slopes may require special methods for stabilization against landslides induced by the slick surfaces of some wet cover materials.

In arid regions, gravel or cobbles are sometimes used in the cover soil layer for erosion control. These covers may not support vegetation and can result in significant volumes of precipitation percolating below the cover into the drainage layer. Concrete covers are sometimes used, but they often leak substantial volumes of water. Asphalt is sometimes used as surface cover, but it requires protection from sunlight and oxidation.

A layer of cobbles may be placed below the soil cover layer to form a barrier to plant roots and burrowing animals; these “biointrusion” layers may be used at sites with radioactive wastes. Although animals cannot generally penetrate a flexible membrane cover (FMC), they can widen an existing hole or tear through wrinkled material (Karr et al., 1992). Gee and Ward (1997) reported that animal burrows did not significantly affect percolation of water into landfill covers at Hanford, Washington. A biointrusion layer is not included as a component in most landfill covers.

3.2.1.2 The Drainage Layer

Water that penetrates through the cover soil and is stopped by the barrier layer is removed laterally by a drainage layer built of highly permeable material. Rapid drainage (1) reduces the head on the underlying barrier layer, thus reducing infiltration, (2) provides aeration for the plant roots growing in the cover soil, and (3) reduces pore water pressures, thus improving slope stability. The most common materials used for the drainage layer are sand and gravel. Geosynthetic materials are also used. All drainage materials must be separated from the overlying soil by adequate filters or filter fabrics.

Geotextiles are flexible, permeable materials usually manufactured from manmade fibers. Some of them are used as filters to prevent the movement of soil particles into drainage systems. Geotextile filters should be placed over the drainage layer to prevent clogging of the latter by fine soil particles. Geonets are manmade drainage layers that are thin and have a grid-like character that provides extensive flow opportunity. McBean et al. (1995) give an example of a 4.5-mm thick geonet having a transmissivity equivalent to 0.3 m of sand. The use of geonets can substantially reduce cover thickness, and they are easier to place than sand layers. The properties of geosynthetic materials suitable for use in drainage layers are discussed in greater detail by Koerner and Daniel (1997).

3.2.1.3 The Barrier Layer

The hydraulic barrier layer is naturally the central element of conventional landfill covers using barrier technology. The barrier layer minimizes percolation of water from the overlying layers into the waste by opposing the natural flow of water downward in response to gravity. The barrier layer is often referred to as an "impermeable" layer although no material commonly used as a barrier is impermeable when new, and most of them deteriorate with age. As a result, the drainage layer lying above the barrier is a required element of the cover; it should quickly remove any water that accumulates above the barrier.

The CCLs are normally constructed from soils rich in clay, and are the most commonly used barrier layers. CCLs are typically about 24 inches thick and have a saturated hydraulic conductivity (K) equal to or less than $1x10^{-7}$ cm/sec. CCLs are constructed in layers (called "lifts") using naturally clay-rich soils. CCLs used in final cover systems should remain ductile to accommodate differential settlement and must be protected from desiccation to reduce cracking, which increases the K value. Because freezing and thawing can also greatly increase the K value, CCLs should be protected from freezing. Where suitable soils are not available, bentonite (a refined, sodium-saturated clay) may be added to native soils to achieve the required K value. Compaction, which is necessary to decrease the porosity of the soil, is dependent on the water content of the clay. The minimum K value is normally associated with maximum compaction, which is achieved in a relatively narrow range of moisture content. The optimum water content of clay for compaction must be determined for each clay source. Koerner and Daniel (1997) provide a more complete discussion of CCLs and their construction. They caution that *"it is easier to build a low-hydraulic-conductivity CCL than it is to design a final cover system that will adequately protect the CCL from forces that tend to drive the conductivity above the design value."*

Other materials can be used singly, in combination with each other, or with a CCL. Where two or more barrier layers are used in combination, the barrier is referred to as a composite barrier.

Geomembranes (GMs) are composed of synthetic materials, and when used as barrier layers in landfill covers are also called flexible membrane covers (FMCs). FMCs are not usually exposed to leachate, so chemical compatibility is not an issue. However, FMCs are subject to substantial strains due to settlement of the waste and must resist penetration by construction equipment, rocks, and roots. Therefore, their strength and elasticity are important properties. They are often required to be at least 40 mils thick to provide adequate strength and other properties.

The most common GMs in use as final covers are constructed of the following materials:

- High-density polyethylene (*HDPE*)
- Linear low-density polyethylene (*LLDPE*)
- Polypropylene (*PP*)
- Polyvinyl chloride (*PVC*)

Some of the properties of these materials are summarized in Table 2.

Table 2. Some Properties of Synthetic Materials Used in Landfill Covers (American Society of Civil Engineers, 1997)

Material	Leachate Compatibility	Biaxial Strain	Seam Integrity
HDPE	Very good	Poor	Good
LLDPE	Good	Very good	Very good
PP	Very good	Very good	Very good
PVC	Good	Very good	Very good

GMs typically have few pinholes and vapor diffusion is very slow, so that little water moves through the material. Installation mishaps, however, may result in punctures, tears, or incomplete seams, which are likely to allow the passage of some water through the barrier layer. Field seaming is a critical factor in GM performance because FMCs arrive on-site in 6-15 m-wide rolls, making field seaming a very large endeavor. The seams should obviously not leak, but in addition should also be physically strong and maintain their integrity over a long period of time. Temperature is an important consideration during FMC installation, and may seriously impact the installation schedule. Installation is usually restricted to periods when the ambient temperature is in the range of 5°C–40°C.

Geosynthetic clay layers (GCLs) are manufactured rolls of bentonite clay held between geotextiles or bonded to GMs. Most sodium bentonite GCLs have K values near $1x10^{-9}$ cm/sec. Koerner and Daniel (1997) conclude that GCLs are generally equivalent or superior to CCLs in final covers, with the exception of field installation issues.

3.2.1.4 The Gas Collection Layer

The decomposition of wastes in a landfill produces gases, some of which are toxic or flammable. A good discussion of the decomposition process may be found in McBean et al. (1995, Chapter 4). Aerobic biological processes occur when oxygen is available to the waste, generally immediately after its disposal. The primary gaseous product of this activity is carbon dioxide. After oxygen is depleted from the waste zone, anaerobic bacteria become dominant and both carbon dioxide and methane gas are produced. Lesser components of landfill gas include hydrogen sulfide, nitrogen, and hydrogen. In addition, any volatile organic compounds in the deposited waste—or produced by later chemical reactions—may be present in landfill gas.

The presence of explosive or toxic gases underground presents a potential problem to nearby buildings and/or to personnel working in the vicinity of the landfill. Gases follow preferential flow paths upward and laterally, either venting ultimately to the atmosphere or accumulating under a natural or manmade resistant layer. To prevent such an occurrence, gases are often collected via active or passive systems and vented in a controlled manner. Any cover that employs a barrier layer is likely to require expensive gas control systems because the barrier may trap gas below the cover. Even low gas-production rates may yield dangerous volumes of explosive and/or poisonous gas if it can be trapped below a barrier within the cover.

The rate at which municipal waste generates gas increases for the first 5 or 6 years after placement in a landfill and declines thereafter. The rate of gas production depends on many factors, but because many military landfills have been inactive for years when finally covered, they are likely to produce only small amounts of landfill gas after cover placement. The placement of a cover will inherently reduce the rate of gas production because the intent of the cover is to stop water from moving into the waste. Biological activity and gas production will decline as the waste dries. Therefore, the use of alternative covers without gas controls may be a viable alternative for military landfills and has the potential advantage of reducing remediation costs. Gas control in landfill covers is discussed in greater detail in Section 3.3.2.

3.2.2 RCRA Subtitle D Covers

RCRA Subtitle D covers are modified, barrier-type covers (see Figure 4). From the surface downward, these covers include a grass cover, topsoil layer, and a layer of undefined soil that is compacted to yield a K value of 1×10^{-5} cm/sec (Ankeny et al., 1997 and Warren et al., 1997). The subtitle D cover meets the federal criteria for Municipal Solid Waste Landfills, 40 CFR, Part 258.60, Closure Criteria. This cover—which may also be called a compacted soil cover—is less expensive than conventional barrier-type covers and has been approved by regulators for use in dry climates. It is a barrier cover (1) because it relies on compaction to create a layer of soil with reduced K value and (2) the topsoil layer is generally no more than 6 inches thick. However, it does not ensure long-term protection against infiltration of precipitation into the waste because freezing and root activity are likely to increase the K value of the soil over time. Because there is no requirement for water-holding capacity within the soil cover, after the soil is loosened by freezing and root activity, the cover may not control movement of precipitation into the waste if the plant-available soil water-holding capacity is low.

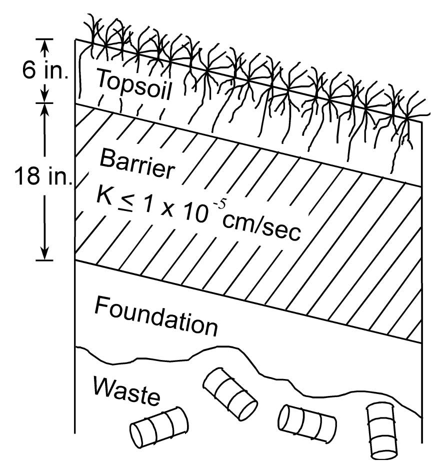

Figure 4. Subtitle D Cover

3.2.3 Innovative Barrier-Type Landfill Covers

Innovative landfill covers discussed here have all undergone at least experimental verification in field tests. Some of them have not been used on large areas. The discussion is brief for those with the most complete descriptions in the literature.

3.2.3.1 Capillary Barriers

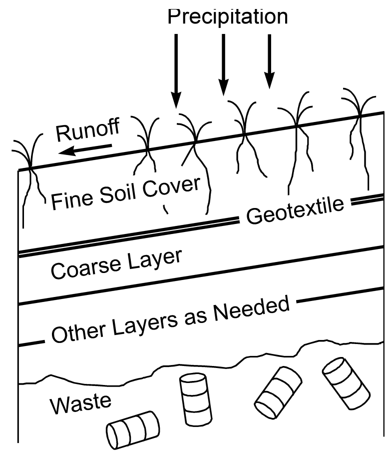

Figure 5. The Capillary Barrier Cover

These covers (see Figure 5) consist of a series of layers, including (from the surface downward) a layer of fine soil over a layer of coarser material (e.g., sand or gravel). The barrier is created in this type of cover by the large change in pore sizes between the layers of fine and coarse material (Stormont, 1997; Gee and Ward, 1997; and Ankeny et al., 1997). Capillary force causes the layer of fine soil overlying the coarser material to hold more water than if there were no change in particle size between the layers. However, this type of barrier can fail if too much water accumulates in the fine-particle layer, thus causing release of water into the coarser layer beneath it. This barrier will be breached under these conditions because the coarse layer provides no barrier to water flow. Lateral drainage, evaporation, and/or plant transpiration remove water stored in the soil above this type of barrier. It has been used primarily in experimental installations.

A capillary barrier is effective if the combined effect of ET and lateral diversion exceeds the infiltration from precipitation, thereby keeping the system sufficiently dry so that appreciable breakthrough does not occur. These systems have been suggested for application in dry climates.

Whereas capillary forces in the soil prevent breakthrough of the water into the gravel at soil moisture conditions less than saturation, when saturation occurs, breakthrough of water will take place and the capillary barrier fails. By placing the interface between the soil and gravel on an incline, lateral flow at pressures less than atmospheric pressure can occur, thus reducing the potential for saturation of the fine layer. Stormont (1996) found that alternating fine and coarse layers were effective over lateral distances of 7 m on a 10-percent slope. He also found that a single barrier layer failed under the conditions of his tests.

The advantage of capillary barrier systems over clay hydraulic barriers is that they are not subject to desiccation and cracking and they may be less expensive to install. Experimental field experience with soil-gravel capillary barrier systems shows that they may fail periodically (Nyhan et al. 1990, Warren et al. 1996).

3.2.3.2 Dry Barriers

As illustrated in Figure 6, the dry barrier cover system—sometimes called the convective air-dried barrier—is similar to the capillary barrier cover except that wind-convective or power-driven airflow through the layer of coarse material helps remove water that may infiltrate this layer (Ankeny et al., 1997). Dry barriers may be suitable for landfills in hot, arid climates. They have been used as a component of other covers in experimental systems.

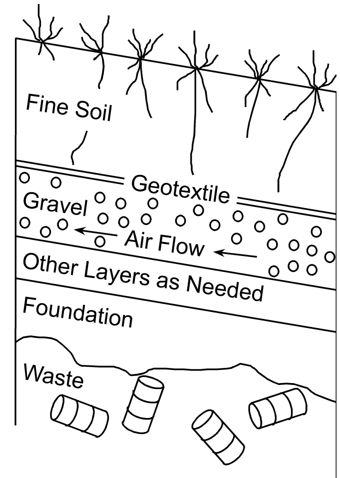

Figure 6. The Dry Barrier Cover

3.2.3.3 Asphalt Barriers

Asphalt barriers may replace compacted clay in arid climate landfills where a clay barrier may fail because of desiccation (Gee and Ward, 1997). This barrier layer is still experimental and is proposed as a rather costly alternative barrier for use in landfill covers over radioactive wastes.

3.2.4 Innovative Landfill Covers without a Barrier Layer

Because of the known water-holding properties of soils and the fact that most precipitation returns to the atmosphere via ET, it should be possible to devise cost-effective covers that meet the requirements for remediation, yet contain no barrier layers. This is especially true for arid and semi-arid regions where evaporation greatly exceeds precipitation. Landfill covers should be capable of preventing precipitation from reaching the waste by storing water in a soil cover until withdrawn by ET.

3.2.4.1 Soil-Plant Landfill Covers

Several investigators (Anderson, 1997) have examined landfill covers that utilize soil and plants but no barrier layer. They are called by several names including soil-plant covers, natural covers, earthen barriers, monofill covers, or monocovers. These covers usually employ a layer of soil on top of the landfill on which grass, shrubs, or trees grow for the purpose of controlling erosion and removing water from the soil. Even though success was expected, a large number of these covers failed to meet the requirements for a landfill cover by allowing too much water to infiltrate into the covered waste.

Anderson (1997) summarized several recent experiments. He stated that *"…failures of earthen barriers as final caps on landfills in arid or semiarid regions likely result from insufficient depths of soil to store precipitation and support healthy stands of perennial plants."* Requirements for success are discussed below and the probable cause for failure of some experimental covers is explained in section 3.4.4.

3.2.4.2 Cover with Modified Surface Runoff

Schulz et al. (1997) describe an experiment in which the amount of surface runoff was controlled by placing aluminum and fiberglass panels on the surface of the landfill cover. The panels were arranged to carry a large part of precipitation off the landfill cover, thus limiting the amount of water that infiltrated into the soil. Between the panels, they planted Pfitzer junipers. The plots were located in Maryland where the annual precipitation is about 1,120 mm and annual evaporation is only 890 mm. Surface runoff from the plots was about 57 percent of precipitation, and there was no deep percolation below the 3-m depth of the soil in the plots. The covers apparently met the requirement for keeping the waste dry.

Both construction and long-term maintenance cost would be high for this type of cover. A monoculture of plants is vulnerable to disease or insect attack; thus the plant cover is not reliable. As a result, the cover described by Schulz et al. (1979) appears to have limited use for Air Force landfills.

3.2.4.3 The ET Cover

The ET cover consists of a layer of soil covered by native grasses; it contains no barrier or impermeable layers. Figure 7 illustrates the concept. The ET cover uses two natural processes to control infiltration: (1) soil provides a water reservoir and (2) natural evaporation from the soil plus plant transpiration (ET) empties the soil water reservoir (Hauser et al., 1995; and Hauser et al., 1996). The ET cover is an inexpensive, practical, and easily maintained biological system that will remain effective over extended periods of time—perhaps centuries—at low cost.

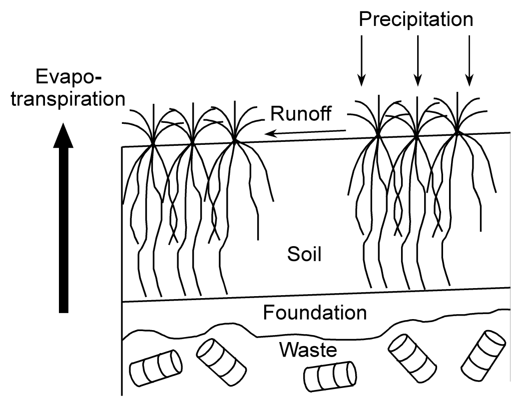

Figure 7. An ET Cover

Climate is a primary determinant as to whether or not an ET cover is practical for a given site. The evaporation-to-precipitation ratio is naturally most favorable in arid and semi-arid areas. Hauser et al. (1994) surmised that when properly designed, ET covers could prevent infiltration into landfill wastes in most of the United States west of the Mississippi River and can minimize infiltration at numerous landfills in much of the rest of the country (Figure 8).

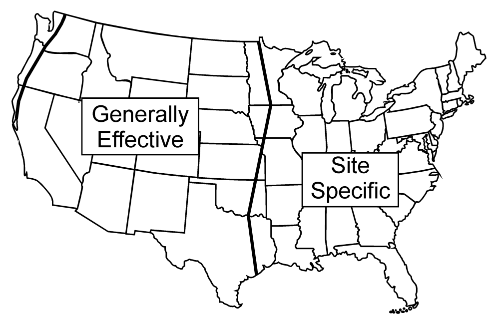

Figure 8. Regions Where ET Covers Are Effective

Successful use of the ET cover requires good engineering design. The ET cover differs from other soil vegetative covers because it has the following minimum criteria:

- The soil physical properties must allow the most rapid and complete root growth possible for the plants growing on the cover. Good physical properties require a soil bulk density between 1.1 and 1.5 g/cm^3. (Bulk density should be adjusted downward if indicated by site conditions.)
- The plant-available soil water-holding capacity of the soil profile must be great enough to hold all soil water accumulated during critical design periods.
- The soil nutrient store and the plant-available nutrients should be adequate to support robust plant growth both immediately and for decades into the future via nutrient cycling within the ecosystem.

- The vegetation growing on the cover should be a mixture of grasses that are native to the site. Grass cover is specified because grass usually provides the optimum erosion control; however, for sites at which grasses are not the dominant native plants, the design should be modified appropriately.

The ET technology was developed and tested within the agricultural engineering and science professions. The principles were well understood years ago by hydrologists, plant and soil scientists, and agricultural engineers. Only in the last decade, however, has this knowledge been brought to bear on the problem of covering landfills and other wastes. Studies by Anderson et al. (1993), Hauser et al. (1994, 1995, and 1996), Nyhan et al. (1990), and Waugh et al. (1994) indicate that soil-vegetative landfill covers will prevent infiltration under appropriate site conditions. Proof of the long-term reliability of the ET cover concept is found in Cole and Mathews (1939), Aronovici (1971), Sala et al. (1992), and Lotspeich et al. (1971). Hauser and Chichester (1989) report the results of an intensive eight-year experiment with mine spoil covers that support the reliability of the concept. If properly designed, built, and maintained, the ET cover can control or prevent movement of precipitation into stored wastes.

Hauser and Weand (1998) used Air Force data to estimate the potential cost savings resulting from using the ET cover rather than conventional barrier-type covers at sites where it would meet the requirements for a landfill cover. They estimated that application of the ET cover on currently unremediated Air Force landfills could result in potential savings of more than $500 million in landfill-cover construction cost.

3.2.5 Summary of Air Force Landfill Cover Alternatives

Conventional, barrier-type landfill covers comprise nearly all landfill covers in place today; they are often accepted as presumptive remedies, but they are expensive. Based on seven covers installed by the Air Force, costs varied from $318,000 to $571,000 per acre of surface (Hauser and Weand, 1998). These designs place a barrier layer within the cover that is intended to prevent water from moving downward in response to the force of gravity. Compacted clay and synthetic materials are common components within barrier-type covers. These covers may be used in all climates and are especially appropriate for use where precipitation equals or exceeds evaporation demand. However, it should be noted that even though they are widely accepted by regulators and others, it is clear that these barriers are not impermeable and that their performance can be expected to degrade with time.

The subtitle D cover—a modified barrier cover that is also called a compacted soil cover—is often accepted by regulators for use on landfills containing municipal solid waste. Therefore, it should be acceptable on many Air Force landfills, particularly in regions where evaporation equals or exceeds precipitation. These covers are significantly less expensive to build than conventional barrier-type covers and should be considered as an alternative for Air Force landfills. Because the barrier is moderately permeable and the soil layer has limited water-holding capacity, these covers may be less effective than other alternative covers.

The capillary barrier works in concert with a cover layer of fine soil that allows plant roots to grow. The purpose of the capillary barrier is to increase the water-storage capacity of the fine soil layer. It is particularly advantageous in locations where soils with high water-holding capacity are unavailable or too expensive. The amount of water that can safely be held in the soil above the barrier is a function of the fine-soil properties and the completeness and effectiveness of the barrier. Experimental capillary barrier systems have sometimes failed when too much water accumulated above the barrier. Therefore, these innovative barriers require careful engineering design and construction to ensure that they will be effective. Although many of the principles required for design are understood by soil scientists and physicists, engineering a design of a robust system may require further development. Capillary barrier covers should be considered for use by the Air Force, but implementation will require careful selection of the design and construction team, and it should be viewed as an experimental cover.

Dry barriers appear to be an improved version of a capillary barrier; they are particularly desirable in situations where the capillary barrier may fail. However, the literature did not address the water-holding capacity of the coarse layer (it will be small) or the airflow rate required to remove the water as it infiltrates the coarse layer. Dry barriers appear to hold promise, but the literature search did not reveal sufficient engineering design data to encourage its use except on an experimental basis.

Asphalt barriers do not appear suitable for widespread use on Air Force landfills. They may be suitable for experimental use.

Soil-plant landfill covers were discussed separately from ET covers although there are many similarities between them. The soil-plant landfill covers described in the literature often were not designed with sufficient water-holding capacity to withstand a series of severe storms. Furthermore, during construction of the soil-plant covers, the soil was sometimes compacted sufficiently to limit or prevent adequate root growth.

The ET cover concept differs from the other innovative covers in two important ways: (1) it uses natural systems and no barrier layers, and (2) the concept has been widely field-tested over long periods of time. The ET cover concept differs from the soil-plant cover because it specifically provides adequate soil water-holding capacity and soil that supports rapid, robust root growth. The design principles for the ET cover are well known, and the potential cost savings to the Air Force are substantial. However, an ET cover design must be carefully evaluated for a specific site to determine if it can meet performance requirements for a landfill cover at that particular site.

3.3 Landfill Cover Design Elements

There are many design elements that must be considered in planning a final cover configuration. This section covers those that are most important to final cover design for Air Force landfills:

- Water balance and infiltration control
- Gas emissions control
- Slope stability
- Erosion control and surface water management
- Vegetation
- Settlement and subsidence

- Filter design
- Bottom liners
- Reuse of landfill areas
- Other design issues

3.3.1 Water Balance and Infiltration Control

A landfill cover minimizes the infiltration of water into underlying waste, with the subsequent possible production of leachate and the threat of groundwater contamination. Only a portion of the water that reaches the cover as rain, snow, or sleet actually infiltrates the surface layer. Much of the water is removed as surface runoff or evaporation. Soil water is subject to loss by ET and can also be diverted laterally by drainage layers incorporated into the cover design. Conventional barriers such as GMs and CCLs—as well as innovative designs such as ET covers—are designed to prevent infiltrated water from percolating through the waste. A general view of this process is illustrated in Figure 9. As a consequence of the principle of conservation of mass, the water flowing into a landfill cover must equal the sum of the flow out of the cover plus any change in water stored within the cover. Such an analysis is termed a "water balance" and is used to evaluate and design landfill cover systems.

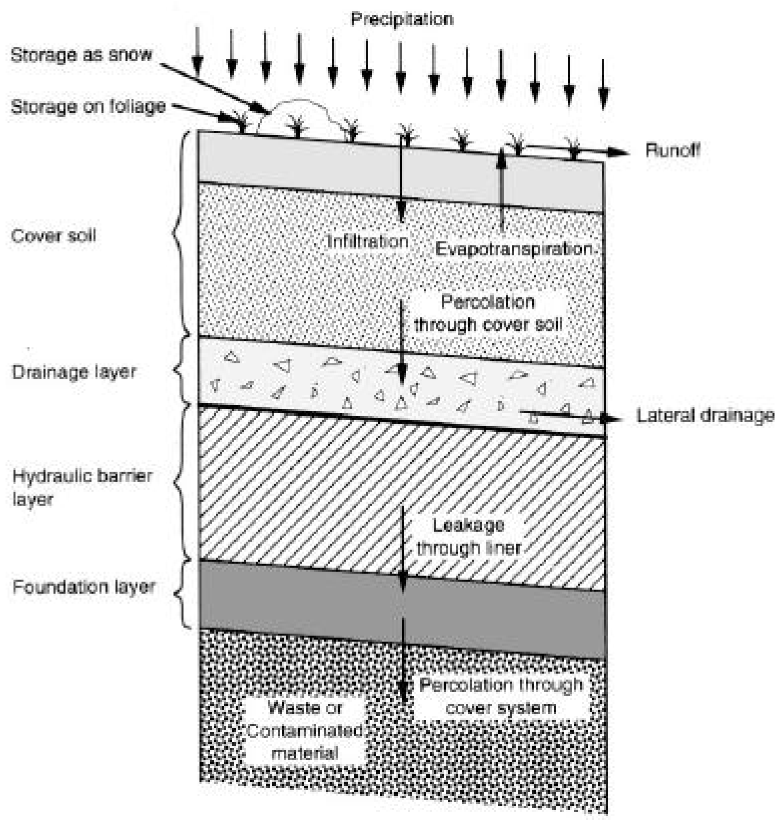

Figure 9. Water Movement Through a Typical Landfill Cover [after Koerner and Daniel, 1997]

The principles of a water balance analysis for a landfill cover are described in detail by Koerner and Daniel (1997), McBean et al (1995), and McAneny et al. (1985). Some of the processes examined are interception of precipitation by vegetation, storage of snow at the surface, runoff, water storage in soil, ET, lateral drainage, and movement through conventional barriers such as GMs and compacted clay. Although they describe how the analysis may be done by hand, nearly all such analyses today are accomplished using computer models. Because the landfill cover is required to be protective over long time periods, the design should be based on the most critical event that may be expected to occur in long time periods (30 to 100 years). The critical event produces a design maximum stress on the cover. This requirement mandates the use of computers to handle large climate databases, generate stochastic climatic events, and estimate daily landfill cover response over decades in order to identify the expected critical event and evaluate the cover response to that event.

HELP is the prevalent computer model used for landfill cover designs. It was developed by the U.S. Army Corps of Engineers Waterways Experiment Station under EPA sponsorship (Schroeder et al., 1994). One of the primary functions of HELP or any other model used in cover design is estimation of the water balance for the landfill. The model uses weather, soil, and design data and processes them through various algorithms to account for water balance over time. The model accounts for the effects of surface storage, snowmelt runoff, infiltration, ET, vegetative growth, soil moisture storage, lateral drainage, leachate recirculation, vertical percolation, and leakage through hydraulic barriers. The HELP model was created to model hydrologic response of landfills having a modern double liner in the bottom of the landfill. It places great emphasis on the movement of liquids below the cover and was originally tested extensively and refined to produce accuracy in estimating water balance in the waste, escape through the liner, and volume and rate of water collection in the liner drainage system. Clearly, the emphasis in the HELP model was the response of manmade systems and waste material lying below the soil cover.

Fleenor and King (1995) found that although the HELP model is effective in simulating water flux through a barrier layer in humid areas, it has a propensity for overestimating the same in arid and semi-arid climates. A field-scale study of earthen landfill final covers (Benson and Pliska, 1996) revealed that HELP underpredicted runoff and overpredicted percolation. They also pointed out that the use of HELP to evaluate and compare conventional barrier covers against innovative covers—particularly in arid or semi-arid environments—could lead to the wrong decision. Khanbilvardi et al. (1995) also determined that HELP underestimated surface runoff in their study of Fresh Kills Landfill in New York. Othman et al. (1995) found that HELP sometimes predicted too much and sometimes too little percolation into the waste. Sharma and Lewis (1994) state *"the model [HELP] has been a valuable tool in predicting leachate generation rates."*

Koerner and Daniel (1997) state that *"[o]ne way that the [HELP] program can be misused is to demonstrate whether or not leachate will be generated during the period in which a landfill is uncovered—whether or not leachate is produced depends almost entirely on the assumption about the initial moisture content of the waste (whether or not it is close to field capacity), and this type of information is usually known with poor accuracy. Thus, in one sense, one could get just about any answer from HELP that one wants, depending on the key assumption about the initial water content of the waste."*

Recently, other models have been used to evaluate percolation through landfill covers; these models include the Unsaturated Soil Water and Heat Flow (UNSAT-H) Model (Fayer et al., 1992) and the Environmental Policy Integrated Climate (EPIC) model (Williams, 1998). Othman et al. (1995) evaluated the Groundwater Loading Effects from Agricultural Management Systems (GLEAMS) and Water Balance Analysis Program (MBALANCE) models. The models UNSAT-H, EPIC, and GLEAMS were developed to solve water-balance problems in agriculture that are similar to those found in landfill covers.

An extensive discussion of models is beyond the scope of this document, but it is apparent that HELP in its present form will not suffice for all the demands being placed upon it. Nevertheless, it remains the model most familiar to regulators and practicing engineers, and so it remains an important influence in landfill design.

A water-balance analysis, usually involving a computer model, is a critical component of landfill cover design. In particular, predicted percolation through the cover is used to assess the protectiveness of the cover, as well as the generation of leachate; these factors will affect other downstream design requirements. Koerner and Daniel (1997) recommended that a standard be implemented for expected percolation rates through landfill cover systems. This standard would provide a quantitative means of evaluating innovative cover designs against the conventional barrier designs that are prevalent today. In this regard, they warn:

> *It is naïve to think that covers will yield zero percolation. Some percolation should be expected. As a starting point, one may wish to note that continuous leakage at unit hydraulic gradient through an intact clay layer with a hydraulic conductivity of 1 x 10^{-7} cm/s yields a percolation rate of about 25 mm/yr (1 in/yr). Non-engineered covers composed of a thin layer of soil probably yield percolation rates of 100 to 300 mm/yr in humid areas. Well-engineered covers almost certainly will reduce percolation rates to no more than 1 to 10 mm/yr, and probably far less (<1 mm/yr) for the most sophisticated designs employing a thick cover soil, a drainage layer, and a GM/clay composite barrier.*

3.3.2 Gas Emissions Control

The production of landfill gas (LFG) is a result of the microbial breakdown of organic matter in the waste. In the initial stages, this biodegradation occurs under aerobic conditions, and carbon dioxide is the principal gaseous product. When the oxygen supply in the vicinity of the waste is depleted, anaerobic organisms become active and methane is eventually generated. After achieving steady-state conditions, which may take several years, LFG will be composed of approximately equal portions of carbon dioxide and methane, along with small amounts of hydrogen, hydrogen sulfide, and other flammable or toxic gases (McBean et al., 1995). Production rates are typically in the range of 0.03-0.20 cubic feet per pound of waste on an annual basis (California Integrated Waste Management Board, 1989), and are dependent on several factors:

- Waste composition and amount (only biodegradable wastes produce gas)
- Oxygen availability (methane is formed only under anaerobic conditions)
- Moisture content (maximum production occurs when the moisture level of the waste is 50-80 percent wet weight)
- Landfill cover (control of infiltration affects the moisture content)
- Soil pH (optimum is 6.5-8.0 for methane bacteria; most landfills are initially more acidic)
- Temperature (methane production decreases markedly below about 50^{o}F).

The microbial production of landfill gases (primarily methane and carbon dioxide) results in an increase in gas pressure within the landfill. Gases are then driven from the waste area into the surrounding soil environment under a pressure gradient. A second mechanism for gas movement is simple diffusion. The migration of landfill gas is an important safety concern because methane gas—one of the principal constituents of landfill gas—is explosive at concentrations between 5-15 percent by volume in air (McBean et al., 1995). RCRA regulations require that combustible gas concentrations shall not exceed the lower explosive limit (LEL) of 5 percent at or beyond a landfill property boundary. Methane will not explode in the landfill itself because there is insufficient oxygen. An explosion hazard develops when landfill gas migrates from the landfill and mixes with air in a confined space, such as crawl spaces, basements, or utility ducts and vaults. There are examples where such migration has produced explosions resulting in extensive property damage and even loss of life.

Beyond the immediate safety issue, landfill gases pose other problems. Vapors of toxic materials, particularly at hazardous waste sites, can pose a health threat to organisms (including humans) if they accumulate in the environment. Hydrogen sulfide—a product of anaerobic waste decomposition at even municipal waste sites—is toxic at concentrations of only 20 ppm (McBean et al., 1995). Landfill gases can also adversely affect vegetation by creating anoxic conditions around the root zone. Such vegetative stress has direct and adverse effects on erosion control measures for the landfill and the degree of water infiltration.

Gases flow in all directions from the refuse, following the paths of least resistance. Lighter-than-air gases will naturally trend upward, and if unimpeded, they will migrate into the atmosphere within 15 meters of the site (McBean et al., 1995). The soil profile adjacent to the landfill will have a profound impact on the lateral movement of the gases. If clay and sand layers are interspersed, for example, the clay may restrict the upward movement of the gases while they follow the sand seams laterally. The presence of features such as buried trenches and conduits will also provide opportunity for preferential flow. Freezing of the ground, ice cover, or saturation of surface soils will act as a temporary barrier to upward movement and increase the lateral flow of landfill gases. The presence of a barrier layer will likewise encourage the accumulation and lateral movement of landfill gases below the barrier. Therefore, barrier-cover technologies usually require the incorporation of a gas collection layer in the cover design. Since gas generation can continue over a long period of time (70 to 90 years) under some circumstances, gas collection and removal systems must work for at least that long to avoid gas-pressure buildup on the underside of the cover (California Integrated Waste Management Board, 1989).

There are two general approaches to gas control in landfills: passive and active systems. Passive systems use vent pipes, trenches, or membranes to convey the gases to the atmosphere. The gas pressures within the landfill provide the driving force for the gas movement. Active gas protection systems employ extraction wells and fans or blowers to draw gases from the landfill area. A description of variations in these approaches, along with their limitations, is provided in a report by the California Integrated Waste Management Board (1989).

According to McBean et al. (1995), active gas removal systems are usually preferred under any of the following conditions:

- The refuse is less than 20 years old.
- The refuse depth is greater than 10 m.
- The property to be protected is less than 0.5 Km from the landfill boundary.

Sand and gravel are the most common materials used in gas collection layers. Any material will need to be kept in a relatively dry state in order to maintain a high permeability to gas. A filter may be needed to separate the sand or gravel from overlying materials, depending upon the materials involved. Designs that employ a geonet drain and geotextile fibers for the gas collection layer can be equivalent to sand and gravel layers. Further details on gas management systems may be found in publications by Landreth et al. (1991), U.S. Environmental Protection Agency (1991) and Koerner and Daniel (1997).

The rate at which municipal waste generates gas increases for the first 5 or 6 years after placement in a landfill, and declines thereafter. Figure 10 shows a typical rate-of-gas production curve under conditions sufficiently wet to permit high decay rates. After placement of an adequate landfill cover, the waste will likely become too dry to maintain these rates of gas production. McBean et al. (1995) used results of typical field studies to show that, after 15 years of landfill inactivity, between 60 and 85 percent of the potential methane production from landfill waste has already been produced. During the time before placement of a cover, the waste in a typical Air Force landfill is likely to remain wet and decay rapidly because the temporary covers that are commonly used allow part of the precipitation to pass through the cover and into the waste. Because most Air Force landfills are more than 20 years old, they are likely to produce only small amounts of landfill gas after cover placement because much—perhaps most—of the decay and concomitant gas production occurred before remediation. The placement of a cover will inherently reduce the rate of gas production because the intent of the cover is to stop water from moving into the waste. Biological activity will gradually dry the waste due to heat production and because the gases produced will carry off the moisture. Therefore, alternative covers that do not include barrier layers may need no gas control and have the potential to reduce remediation costs.

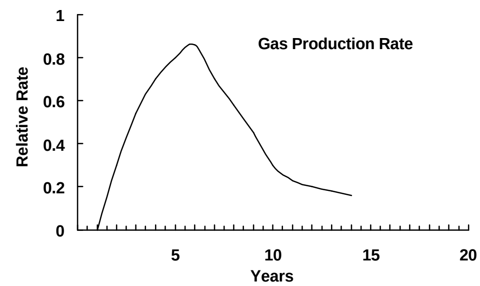

Figure 10. Typical Rate of Landfill Gas Production

3.3.3 Slope Stability

A landfill cover may be susceptible to instability from lateral movement, particularly when slopes are steep. The principal ways to improve stability focus on surface water management (see Section 3.3.4) and strengthening the cover through the use of a retaining system. Specific methods are detailed by Lutton (1987) and by Koerner and Daniel (1997).

Slope failures on final covers may be caused by three destabilizing agents: weight of the wastes and cover materials, seepage forces caused by water infiltration, and seismic forces. Koerner and Daniel (1997) state that most cover slope failures are related at least in part to seepage problems. The modes of possible slope failure are through translational forces along cover layer interfaces, translational forces through weak soil layers, and rotational failures with surfaces passing through the cover system and underlying wastes. A report by the California Integrated Waste Management Board (1994) presents various analytical techniques for evaluating the stability of covers. Richardson and Kavazanjian (1995) detail techniques to evaluate landfills for seismic risks.

Modern landfills maximize waste thickness to best use the available “air space,” which results in steep cover slopes (air space is the aboveground, vertical dimension available for waste disposal—the higher it is, the more waste can be planted on a given footprint). Slopes of 3H:1V (ratio of horizontal to vertical) are common, and even steeper slopes of 2H:1V have been used (Koerner and Daniel, 1997). Common barrier materials such as GMs and hydrated GCLs have low interface shear strength and increase the concern about instability. Furthermore, the use of geosynthetics for drainage and gas collection layers creates potential shear planes.

Koerner and Daniel (1997) list the most common failures:

- Cover soil slides off the upper surface of a smooth GM.
- Cover soil with an underlying geotextile of drainage geocomposite slides off the upper surface of a smooth GM.
- Cover soil, drainage materials, and underlying GM slide off the upper surface of the underlying soil.
- Cover soil, drainage materials, and underlying GM slide off the upper surface of an underlying hydrated GCL, particularly if the upper surface of the GCL is woven slit film geotextile.

Air Force landfill covers usually have relatively flat slopes, so slope stability is not typically a major problem. However, slope stability should be evaluated for all landfill cover designs. Additional guidance on designing for slope stability may be found in U.S. Environmental Protection Agency (1988), in Koerner and Daniel (1997), and in current textbooks.

3.3.4 Erosion Control and Surface Water Management

Erosion of surface soil from a cover can be a serious problem. Not only can the efficacy of the cover be diminished, but downstream environments can also be adversely affected. One survey indicated 20 percent of the landfills studied were severely eroded, and another 40 percent were moderately eroded (California Integrated Waste Management Board, 1994). Without appropriate drainage controls in the soil above a given layer, the installation of hydraulic barrier layers within the cover can lead to saturated soils and large amounts of surface runoff, resulting in severe erosion.

Inadequate drainage to remove water accumulating above barrier layers can cause severe gully erosion, resulting in loss of all cover over the barrier layers. The affected area may be limited to gullies or encompass several acres, as detailed by Koerner and Daniel (1997) and the U. S. Environmental Protection Agency (1991). Sperling and Hansen (1997) describe erosion of a landfill cover and supporting structures in a semi-arid climate in Canada. The erosion occurred because the drainage system was overwhelmed by a critical runoff event.

The agricultural community has studied erosion in detail for over a half-century, and the factors that affect erosion rates are well understood. The most often used model for soil erosion is the Universal Soil Loss Equation (USLE), which is explained in publications by the U.S. Department of Agriculture (1985) and McBean et al. (1995). The terms that are incorporated into this equation provide insight into the factors that affect erosion: rainfall energy, soil erodability, length of slope and gradient, and vegetative cover. With regard to landfill design, the most important factors are slope and vegetation. Lower slopes reduce the velocity of runoff and its erosion potential; shorter slope lengths reduce the volume of runoff. Slopes of at least 2.5 percent are usually incorporated into a cover design to promote surface drainage, prevent ponding, and provide some allowance for settling and subsidence. All landfill slopes are steep enough to require erosion control.

Vegetation provides both the least expensive and most effective erosion control for landfill covers. Living or dead plant material dissipates rainfall energy and controls both water and wind erosion. A cover of native grasses and forbs provides a self-renewing, natural erosion control system that can function with little or no maintenance for decades or centuries.

A soil cover is most vulnerable to erosion during the time when vegetation is first becoming established after construction is complete. The timing for completion of cover construction in relation to the growing season of the vegetation planted is important. If construction is completed at the end of the growing season, fast-growing annual grasses such as wheat, barley, sorghum, or millet should be established. These temporary covers should be left in the undisturbed state, and the permanent grasses should be seeded into the standing stubble. Temporary erosion control, such as through the use of geotextiles, may be considered for small but critical areas (U.S. Department of Agriculture, 1985).

Cabalka (1996), Othman et al. (1995), McBean et al. (1995) and Koerner and Daniel (1997) discuss erosion control and vegetation establishment. Modern textbooks discuss modern landfills that typically require covers over small mountains of waste with side slopes of 3:1 or 4:1 and surface areas of hundreds of acres. Under these conditions, revegetation and erosion control are both expensive and difficult. The designs for soil stabilization typically employ diversion terraces (under several names), chutes (lined with riprap), stilling basins, benches on side slopes, and engineering structures. These structures can be successful if they are rigorously maintained during every year of cover operation, otherwise, failure is likely. Maintenance of vegetation on the steep slopes may require frequent fertilization and irrigation to maintain healthy stands of even hardy native grasses.

Surface water management structures such as benches, diversion terraces, dikes, ditches, check dams, pipes, chutes, and surface waterways are often recommended for modern landfill surfaces (McAneny et al. [1985], Koerner and Daniel [1997], and McBean et al. [1995]). Structures of this type are often used on modern RCRA-type landfill covers and require regular (at least annual) inspection and maintenance to ensure continued operation.

Air Force landfill surfaces are generally smaller in size than a typical municipal or commercial landfill, and have maximum land slopes of 10 or 12 percent. The requirements for successful erosion control are quite different at these landfills. After establishing an adequate stand of several species of grasses and forbs, erosion by wind and water should diminish to near zero. Structures such as benches, diversion terraces, and chutes are not required on covers of this kind. These covers will simulate natural ecosystems and will be self-renewing.

3.3.5 Vegetation

To reduce erosion and allow transpiration to remove water, nearly all cover designs include the establishment of vegetation on the surface layer. For certain innovative cover designs—such as the ET cover—selecting and establishing vegetation is of critical importance to the cover's ability to prevent percolation of water into the waste. The establishment of vegetation has both short-term and long-term components. It is important to establish vegetation over newly constructed cover systems because it is most vulnerable to erosive processes at this time. Furthermore, the long-term health, viability, and maintenance of the vegetation are paramount because the function of the vegetative layer must be fulfilled for many decades. To encourage the rapid establishment of perennial vegetation, it is important to consider soil type, nutrient and pH levels, climate, species selection, mulching, and seeding time. Specific recommendations related to these factors have been detailed by Lutton (1987), Koerner and Daniel (1997), and McDonald et al. (1996). Schuman et al. (1980) demonstrated the effectiveness of standing small grain stubble as the cover for emerging grass seedlings.

McAneny et al. (1985) and Schuman et al. (1980) point out several important considerations in establishing effective vegetation on landfill covers:

- Use native species.
- Use mixtures rather than single species.
- In dry regions, plant annual grain (wheat, barley, etc.) and maintain the standing stubble as cover for young seedlings.
- Plant immediately ahead of the period of highest expected rainfall probability.

Further guidelines for the successful establishment of vegetation on landfill covers may be found in McAneny et al. (1985), Gilman et al. (1983), and California Integrated Waste Management Board (1994). Flower et al. (1978) conducted a survey and analysis regarding the problems with vegetative growth at landfill sites throughout the United States. They ascribed many of the problems to waterlogged soils and the effects of landfill gas. Although grasses and forbs have been utilized most for landfill vegetative cover, Gilman et al. (1981) investigated critical factors affecting the growth of woody plants at such sites.

3.3.6 Settlement and Subsidence

The harmful impact of settling upon the final cover is primarily due to (1) the resultant tearing or cracking of cover components or (2) the change or even reversal in final cover system slopes. Such occurrences can affect the performance of the drainage and gas collection layers, as well as the overall water balance.

Othman et al. (1995) list three causes of landfill cover settlement: settlement of foundation soils, settlement resulting from overall waste compressibility, and settlement caused by localized mechanisms. While settlement is possible, it is unlikely to be a major concern for military landfills that have been inactive for a long period of time.

3.3.7 Filter Design

Filters are used to prevent excessive migration of soil particles while allowing relatively unimpeded flow of liquid or gas from the soil into a drainage layer or pipe. In landfill covers, filters are often placed above a drainage or a gas-collection layer to prevent it from clogging. Typically, they use one or more layers of granular materials, geotextiles, or a combination of these materials.

Filters must be sufficiently permeable to allow the free passage of liquids or gases, but they must also have small enough void space to prevent the loss of solids from upstream. Also, a filter must not become completely clogged for the duration of its service life. Filters may be clogged by inorganic matter or growth of microbial organisms.

Design of soil filters is based upon particle size distribution and permeability values. Details may be found in Sharma and Lewis (1994) and Koerner and Daniel (1997). Geotextile filter design considerations include compatibility, soil retention, and clogging evaluations, in addition to permeability (Landreth et al., 1991).

3.3.8 Bottom Liners

Modern landfills must have liner systems under the waste to prevent the downward movement of leachate and contamination of the environment. The implications for a final cover system are that it will have to integrate and be compatible with the liner system design and that it may need to meet the Subtitle D requirement—the barrier layer in the cover must have a permeability equal to or less than that of the bottom liner. In the latter instance, this essentially requires the use of a GM in the final cover system. Because less than one percent of Air Force landfills are estimated to have bottom liners (Hauser and Weand, 1998), bottom liners will have little impact on decisions regarding covers for Air Force landfills.

3.3.9 Reuse of Landfill Areas

Land reuse is an important consideration in landfill cover selection. Former landfill sites find new life as parks, golf courses, nature areas, and bicycle paths. However, some uses—such as golf courses—may produce significant liability for the landfill owner.

Nature areas and bicycle paths utilize covers that can maintain the surface soil in the driest state possible for the climate at the site. Therefore, these uses minimize potential for water leakage through the cover. These uses are also aesthetically pleasing to the public. If the landfill produces significant amounts of landfill gas, the gas must be carefully controlled so that it does not pose a hazard to users.

Both bicycle and access paths for nature areas must be built to prevent excessive accumulations of water in the cover. Asphalt, gravel, and concrete walkways each permit some water to move through the surface in addition to lateral infiltration from the edge. Because these walkway surfaces dramatically reduce evaporation from the surface, they may trap water in the cover. Therefore, pathways should be made as narrow as possible, and evaluated on a site-specific basis.

Golf courses are aesthetically pleasing and popular with the public. However, golf courses on top of landfills may have problems including constantly shifting surface grades, dead grass and fires on the surface resulting from landfill gas, and damage to buildings due to subsidence or explosions of landfill gas (Pacelle, 1995).

The long-term—and possibly the most serious—consequence resulting from golf course location on top of landfills results from irrigation, which may cause excessive amounts of water to move into the waste and increase the potential for groundwater contamination. Golf courses are irrigated frequently to maintain the desired quality of turf. The turf is normally irrigated daily, thus providing opportunity for substantial deep percolation into the waste. Deep percolation results from two separate causes: (1) in order to maintain healthy grass, more irrigation water must be applied than used by the grass to leach salts out of the soil, and (2) rainfall shortly after irrigation is highly likely to add substantially to the volume of deep percolation.

Klocke et al. (1996) reported deep percolation from corn and soybean irrigation on a deep fertile soil in Nebraska. They managed the crops to use the least possible water to achieve acceptable crop yields, and the crops were irrigated only during the summer. During a five-year period, they measured between 127 and 193 mm/yr of deep percolation; the amount depended on crop, irrigation treatment, and weather. It is safe to assume that a well-managed golf course will produce much more than 127 mm/yr of deep percolation and that it has potential to enter the waste through any cover discussed in this report.

3.3.10 Other Design Issues

Structures built over landfills require proper connection to the cover layers to maintain the integrity and function of the final cover system. These connections include gas collection pipes, monitor wells, or underground utilities that penetrate the cover. Connections must be designed to account for settlement potential.

When designing a landfill liner, the chemical compatibility of landfill cover materials with the wastes being covered should be considered (California Integrated Waste Management Board, 1994). However, because cover materials normally do not contact the waste, it is of little importance in covers where no corrosive landfill gas migrates upward to the cover.

The type and amount of daily cover can influence final cover design, particularly in regards to the foundation layer. Because the Air Force currently operates virtually no landfills, the reader is referred to modern textbooks on landfills for information on operations, daily cover, etc. (McBean et al., 1995; Kreith, 1994; and Tchobanoglous et al., 1993).

3.4 Case Studies of Landfill Cover Performance

Useful data from long-term monitoring of landfill covers are not available. Some multi-year research studies that have been conducted—primarily on innovative covers—are discussed in Section 3.2. Other information relates primarily to cover failures, but it tends to be anecdotal. Some observations from the literature concerning the actual performance of various cover components are summarized below.

It is important to understand that actual cover performance may differ substantially from either the presumed performance or the perception conveyed by use of descriptive words (such as “*impermeable*”) that are often used when discussing conventional landfill covers. Over time, almost all landfill covers will allow some water to percolate into the waste; the degree to which this occurs is very difficult to measure and seldom reported, except for experimental covers. Cover failures that are easily detected and understood are the result of inadequate gas control, soil erosion, landslides, or slope failure. Adequate design in conjunction with good construction practices can prevent these failures.

3.4.1 Infiltration Through Conventional Landfill Covers

Suter et al. (1993) provide an extensive review of failures and failure mechanisms for compacted soil covers for landfills. They state *"…natural physical and biological processes can be expected to cause [clay] barriers to fail in the long term (>100 yr)."* Their review of published literature included two field-scale tests of newly completed, CCLs; both barriers leaked, and Suter et al. (1993) concluded *"…it was not possible to obtain uniform hydraulic properties in the [clay] liner."* They further stated that *"[c]onstruction of compacted soil barriers without flaws that allow rapid seepage is difficult and perhaps is not a reasonable expectation."*

3.4.2 Cracking in Conventional Clay Cover Barrier Layers

Koerner and Daniel (1997) discussed a field test conducted in Germany that illustrates problems that may occur with CCLs. The test included four barrier-cover designs, each of which was covered by 750 mm of topsoil and 250 mm of fine gravel for drainage. The four barriers were built as follows:

- 600 mm of compacted clay
- Composite layer made of HDPE GM with welded seams over compacted clay
- Composite layer made of HDPE GM with overlapping, non-welded seams over compacted clay
- Compacted clay over 600 mm of fine sand over 250 mm of coarse sand and fine gravel to form a capillary barrier

The covers with composite barriers performed well and allowed no percolation. The CCLs performed well for 20 months. However, during a drier-than-normal summer, the clay layers dried. After the dry summer, percolation through the cover was almost ten times the percolation recorded during the previous year.

Exploratory excavations revealed that small cracks and plant roots had penetrated the clay. Seven years after the beginning of the experiment, percolation through the compacted clay was almost 200 mm/yr and increasing.

3.4.3 Geomembrane Leakage

Leaks in GMs occur primarily as a result of holes left by construction. Board and Laine (1995) found 26 holes in a 4-acre liner. They also reported that 69 percent of the holes were found in the seams.

In Britain, Crozier and Walker (1995) examined 7 GM installations and found holes ranging in size from pinholes to 2-meter gashes. The average number of holes in their study was 2 per acre. They also discussed a study of 17 leak location surveys in the United States that showed an average of 6 leaks per acre, but ranged as high as 15 leaks per acre. They concluded that GM leak detection surveys should be used to supplement construction quality assurance programs.

3.4.4 Misapplication of Vegetative Landfill Covers

Landfill cover design and application should avoid known causes for poor performance. Some experimental covers that were called by various names such as vegetative covers or soil-plant covers failed to meet the requirements for a cover. Most of these covers were tested in arid or semi-arid regions where success was expected.

Anderson (1997) summarized several recent experiments and provided details for one recent test. He stated that *"Past failures of earthen barriers as final caps on landfills in arid or semiarid regions likely result from insufficient depths of soil to store precipitation and support healthy stands of perennial plants."*

Warren et al. (1996) reported the results of a four-year experiment with four landfill covers at Hill Air Force Base in northern Utah. Their experiment included a control plot with soil and vegetation only, a RCRA barrier-type cover, and two capillary barrier covers. The capillary barrier covers were similar to the soil-vegetation cover with two exceptions: the soil was thicker, and they had a capillary barrier under the fine-soil layer. Each of the four treatments was seeded to grass; however, one capillary barrier included both grass and shrubs in the cover. They measured leachate (the water moving into the waste) for 46 months and collected the data shown in Table 3. Leachate amount was unrelated to ground cover or plant biomass.

Table 3. Leachate Production during 46 Months under Four Landfill Covers (Warren et al., 1996). Total precipitation for the period was 2020 mm.

Soil Depth (m)	Treatment	Leachate (mm)
1.2	RCRA, barrier-type	<1
0.9	Soil-vegetation, (control)	410
1.5	Capillary barrier	240
1.5	Capillary barrier (+ shrubs)	300

Because the site is in a dry climate, one would expect both the soil-vegetative and capillary barrier covers to work as well as the RCRA barrier-type cover. The soil-vegetative cover produced more leachate than the capillary barriers, probably because the soil layer was thinner, thus it held less water. The authors note that most leachate was produced when evaporation potential was low during early spring and resulted from snowmelt and early rains; however, they did not discuss the cause for failure. A highly likely cause for failure is presented below.

Warren et al. (1996) reported that they compacted the soil in all treatments, including the soil-vegetation cover, to a bulk density of 1.86 g/cm^3. The soil density was even greater than that of the compacted clay in their RCRA cover (1.76 g/ cm^3). High soil bulk density is known to limit growth of plant roots. Plant roots grow well in most soils having bulk densities of 1.1 to 1.5 g/cm^3, fair or poorly in soils having bulk density up to 1.7 g/cm^3, and poorly or not at all at higher soil bulk densities (Eavis, 1972; Monteith and Banath, 1965; Taylor et al., 1966; Jones, 1983, Timlin et al., 1998 and Gameda et al., 1985).

Water can move rapidly to roots through only a few mm of soil. Soil water more than a few mm away from roots moves slowly, if at all, toward the root surface. Therefore, to ensure rapid, effective water removal from soil, roots must fully explore layers from which water is to be withdrawn by plants. High soil density may have reduced or prevented adequate root growth in the soil profile in these experiments. In addition, soils with high bulk density have a reduced water-holding capacity.

The vegetated covers investigated by Warren et al. (1996) may have failed as a result of one or more of the following 3 mechanisms: (1) inadequate soil depth, (2) reduction of water-holding capacity by soil compaction or (3) poor root growth resulting from soil compaction.

3.4.5 Gas Control

At Glendale, California, a golf course was built on a landfill that had an insufficient cover and no gas control system. Fissures on the golf course and in the asphalt parking lot released methane. Small fires were reportedly ignited in the parking lot by sparks from passing cars. The golf course had to be closed because of excessive methane generation. The course was reopened after being covered with an additional 6 to 15 feet of soil. However, no gas control system was installed, so maintaining healthy vegetation continues to be a problem. The methane in the landfill gas displaces the oxygen in the soil. Because all plants require oxygen in the soil, some areas cannot support grass and shrubs. (Pacelle, 1995)

The absence of gas control coupled with an impermeable GM can also create large gas bubbles that can lift the cover (Koerner and Daniel, 1997).

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Appendix A

RCRA Subtitle C (Hazardous Wastes)
40 CFR 264.310 Closure and Post-Closure Care

(a) At final closure of the landfill or upon closure of any cell, the owner or operator must cover the landfill or cell with a final cover designed and constructed to:

(1) Provide long-term minimization of migration of liquids through the closed landfill;

(2) Function with minimum maintenance;

(3) Promote drainage and minimize erosion or abrasion of the cover;

(4) Accommodate settling and subsidence so that the cover's integrity is maintained; and

(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

(b) After final closure, the owner or operator must comply with all post-closure requirements contained in §§ 264.117 through 264.120, including maintenance and monitoring throughout the post-closure care period (specified in the permit under § 264.117). The owner or operator must:

(1) Maintain the integrity and effectiveness of the final cover, including making repairs to the cap as necessary to correct the effects of settling, subsidence, erosion, or other events;

(2) Continue to operate the leachate collection and removal system until leachate is no longer detected;

(3) Maintain and monitor the leak detection system in accordance with §§ 264.301(c)(3)(iv) and (4) and 264.303(c), and comply with all other applicable leak detection system requirements of this part;

(4) Maintain and monitor the ground-water monitoring system and comply with all other applicable requirements of subpart F of this part;

(5) Prevent run-on and run-off from eroding or otherwise damaging the final cover; and

(6) Protect and maintain surveyed benchmarks used in complying with § 264.309.

Appendix B

RCRA Subtitle D (Municipal Solid Waste, MSW)
40 CFR 258, Subpart F—Closure and Post-Closure Care

§ 258.60 Closure criteria

(a) Owners or operators of all MSWLF units must install a final cover system that is designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:

(1) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/sec, whichever is less, and

(2) Minimize infiltration through the closed MSWLF by the use of an infiltration layer that contains a minimum 18-inches of earthen material, and

(3) Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6-inches of earthen material that is capable of sustaining native plant growth.

(b) The Director of an approved State may approve an alternative final cover design that includes:

(1) An infiltration layer that achieves an equivalent reduction in infiltration.

(2) An erosion layer that provides equivalent protection from wind and water erosion as the erosion layer specified in paragraph (a)(3) of this section.

Appendix C

Texas Natural Resource Conservation Commission
Proposed Chapter 350—Texas Risk Reduction Program
Rule Log No. 96106-350-WS

The Texas Natural Resource Conservation Commission (commission or agency) proposes new §§350.1-350.5, 350.31-350.35, 350.51-350.62, 350.91-350.96, 350.111-350.117, 350.131-350.132, concerning requirements pertaining to off-site properties and leased lands; required actions when substantial changes in circumstances occur at an affected property; the assessment of property affected by chemicals of concern (COCs); the development of protective concentration levels for human and ecological receptors; the performance of response actions necessary to restore a property to active and productive use; the performance of post-response action care; the establishment and maintenance of financial assurance for post-response action care in certain circumstances; reporting requirements; and standardized deed recordation/restrictive covenant language.

Explanation of Proposed Rule

The proposed rule, commonly referred to as the Texas Risk Reduction Program (TRRP) rule, will establish a uniform set of risk-based performance-oriented technical standards to guide response actions at affected properties regulated via the agency's Office of Waste Management program areas and other applicable program areas. The rule will be promulgated as a new chapter (i.e., 30 Texas Administrative Code [TAC] Chapter 350). Currently, several different rules govern corrective actions, closures, and post-closure care within the agency's waste management programs. The State Superfund program, the Industrial and Hazardous Waste program, and the Voluntary Cleanup Program (VCP) use the existing Risk Reduction Rules in 30 TAC Chapter 335, Subchapters A and S for risk-based corrective action. Any person who stores, processes or disposes of hazardous waste is also subject to the closure and post-closure care requirements in 30 TAC Chapter 335, Subchapters E and F. The Petroleum Storage Tank (PST) program uses 30 TAC Chapter 334, Subchapters D and G for risk-based corrective action. Corrective action and closure requirements for operating municipal solid waste landfills subject to federal Resource Conservation and Recovery Act (RCRA) Subtitle D requirements are found in 30 TAC Chapter 330. There are no specific corrective action requirements for other municipal landfills. Corrective action requirements for the Underground Injection Control (UIC) program are found in 30 TAC Chapter 331, Subchapter C. Spill response actions regulated under 30 TAC Chapter 327 that will take longer than six months to complete follow the Risk Reduction Rules or the PST rules, whichever is appropriate for a particular release. Currently, there are no rules for corrective action at compost facilities.

New Chapter 350 is subdivided into Subchapters A through F. Subchapter A—General Information consists of §§350.1-350.5 and sets forth the general requirements of the TRRP rules. Subchapter B - Affected Property Assessment, §§350.31-350.35, establishes the necessary actions for property assessments. Subchapter C—Development of Protective Concentration Levels, §§350.51-350.62, and Subchapter D—Remedy Standards,

§§350.91-350.96, form the basis of the risk-based corrective action process. Subchapter C directs persons to evaluate exposure pathways and determine the concentration of the COC that is protective for human and ecological receptors at the point of exposure (POE) This concentration is referred to as risk-based exposure limits (RBELs). Separate RBELs are established for human and ecological receptors. For example, when a volatile organic compound (VOC) is present in subsurface soils, vapors rise to the surface and are released into the air. The POE to air is where a receptor inhales the vapors. The RBEL is the concentration of the VOC in the air that is safe for the receptor to breathe assuming long-term, chronic exposure.

Persons then derive protective concentration levels (PCLs). PCLs are the concentration limits of COCs in the source media (e.g., soil and groundwater) that will achieve the RBELs in the exposure media. Continuing the example, the PCL is the concentration of the VOC in the subsurface soil that will, based upon modeling of cross-media transfer, achieve the RBEL for breathing the VOC at the POE in air. A tiered process is provided to establish both human health and ecological PCLs: Tier 1, 2 and 3. This tiered process for human health PCLs is patterned after the tiered process of the American Society of Testing and Materials *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites* ES-1739-95. Once PCLs are determined, the person must choose a remedy standard under Subchapter D. The person may choose one of two remedy standards, Remedy Standard A or Remedy Standard B. Remedy Standard A is a pollution cleanup approach and does not allow a person to use either physical or institutional controls, other than requiring a deed notice/restrictive covenant for commercial/industrial land use. Remedy Standard A requires that all media be removed or decontaminated to the applicable PCLs. Remedy Standard B allows exposure prevention approaches which rely on physical and/or institutional controls to protect human health and the environment. Persons may base remedy standards on residential or commercial/industrial land use as appropriate for the particular affected property.

§350.93. Remedy Standard A.

(a) To attain Remedy Standard A, the person shall:

(1) remove any listed hazardous waste as defined in 40 CFR Part 261, Subpart D, which is separable using simple mechanical removal processes;

(2) remove and/or decontaminate any waste or environmental media which is characteristically hazardous due to ignitability, corrosivity, reactivity, or toxicity characteristic as defined in 40 CFR Part 261, Subpart C;

(3) remove and/or decontaminate the soil and groundwater PCLE zones (monitored natural attenuation can be used when appropriate considering the hydrogeologic characteristics of the affected property and chemical-specific data), other environmental media, and non-hazardous waste to the critical residential or commercial/industrial PCLs or source medium PCLs, as applicable; and

(4) demonstrate that remaining concentrations of volatile COCs in the soil or groundwater will not result in vapor concentrations in excess of 25% of the lower explosive limit for the COC or COC mixture within outdoor air, surface or below-ground structures, or within the soil zone extending from ground surface to 15 feet

in depth, or to the typical depth of the construction zone as defined in accordance with §350.2 of this title (relating to Definitions and Acronyms) when it extends to depths greater than 15 feet.

(b) Response actions under Remedy Standard A must result in permanent risk reduction at an affected property. The person shall not use physical controls under Remedy Standard A. The person shall remediate the affected property such that the concentration of COCs in soil and groundwater do not exceed the applicable critical PCLs and the concentration of COCs in surface water, sediment and air do not exceed the applicable source medium PCLs.

(c) The person shall determine the PCLs for Remedy Standard A using source medium exposure pathways where the human or ecological receptor comes into contact with the COCs directly within, above, or below a source medium. Lateral transport exposure pathways using lateral transport equations which place the POE at a location outside of the source area cannot be used to determine PCLs for Standard A response actions with the following exceptions:

(1) to ensure that an off-site resident is protected when the receptor is assumed to be a commercial/industrial worker for purposes of establishing a source medium PCL; or

(2) when development of LT-GW is required in accordance with §350.57(d) of this title SW (relating to Development of Human Health PCLs for Groundwater Exposure Pathways).

§350.94. Remedy Standard B.

(a) To attain Remedy Standard B, the person shall:

(1) remove, decontaminate, and/or control the surface soil, subsurface soil, and groundwater PCLE zones, other environmental media, and hazardous and non-hazardous waste in accordance with the provisions of this section such that human and ecological receptors will not be exposed to concentrations of COCs in the exposure media in excess of the residential or commercial/industrial critical PCLs or source medium PCLs, as applicable, at the prescribed, or any approved alternate, on-site or off-site POEs established for environmental media; and

(2) demonstrate that remaining concentrations of volatile COCs in the soil or groundwater will not result in vapor concentrations in excess of 25% of the lower explosive limit for the COC or COC mixture within outdoor air, surface or below-ground structures, or within the soil zone (beyond the boundaries of an physical control measure) extending from ground surface to 15 feet in depth, or to the typical depth of the construction zone as defined in accordance with §350.2 of this title (relating to Definitions and Acronyms) when it extends to depths greater than 15 feet.

(b) The person performing a response action to attain Remedy Standard B may use removal and/or decontamination with controls or controls only, with the exception of response actions for class 1 groundwater PCLE zones that must be removed and/or decontaminated to the critical groundwater PCL for each COC. The person may use both physical and institutional controls. The person shall demonstrate to the satisfaction of the executive director that the response actions which they propose to use will attain the requirements of subsection (a) of this section within a reasonable time frame given the particular circumstances of an affected property. The person shall also perform any more stringent or additional response actions that are required by the statute or regulations governing the program areas covered by this chapter as specified in §350.3 of this title (relating to Applicability).

(c) PCLs for Remedy Standard B are determined through consideration of both source medium and lateral transport exposure pathways. Lateral transport equations may be used to back-calculate lateral transport PCLs which are applied within the soil and groundwater source areas and will result in the attainment of the critical groundwater PCLs and source medium PCLs for other exposure media at the prescribed, or any approved alternate, on-site and off-site POEs established for environmental media.

Appendix D

California Regulations

§21090. SWRCB—Closure and Post-Closure Maintenance Requirements for Solid Waste Landfills (C15: §2581 // T14: §17777, §17779)
[Note: For SWRCB's final cover performance standard, see §20950(a)(2)(A); for related CIWMB requirements, see §21790 et seq.]

(a) **Final Cover Requirements**—Final cover slopes shall not be steeper than a horizontal to vertical ratio of one and three quarters to one, and shall have a minimum of one fifteen-foot wide bench for every fifty feet of vertical height. Designs having any slopes steeper than a horizontal to vertical ratio of three to one, or having a geosynthetic component [under ¶(a)(2)], shall have these aspects of their design specifically supported in the slope stability report required under §21750(f)(5). The RWQCB can require flatter slopes or more benches where necessary to ensure preservation of the integrity of the final cover under static and dynamic conditions. The cost estimate, under §21769, for the final cover shall include a description of the type and estimated volume (or amount, as appropriate) of material needed for each component of the final cover based upon the assumption that all materials will need to be purchased; if on-site materials are to be used, the submittal shall include test results confirming the availability of such on-site materials and their suitability for such use. The RWQCB [Regional Water Quality Control Board] can allow any alternative final cover design that it finds will continue to isolate the waste in the Unit from precipitation and irrigation waters at least as well as would a final cover built in accordance with applicable prescriptive standards under ¶(a)(1-3).

(1) Foundation Layer—Closed landfills shall be provided with not less than two feet of appropriate materials as a foundation layer for the final cover. These materials may be soil, contaminated soil, incinerator ash, or other waste materials, provided that such materials have appropriate engineering properties to be used for a foundation layer. The foundation layer shall be compacted to the maximum density obtainable at optimum moisture content using methods that are in accordance with accepted civil engineering practice. A lesser thickness may be allowed for Units if the RWQCB finds that differential settlement of waste, and ultimate land use will not affect the structural integrity of the final cover.

(2) Low-Hydraulic-Conductivity Layer—In order to protect water quality by minimizing the generation of leachate and landfill gas, closed landfills shall be provided with a low-hydraulic-conductivity (or low through-flow rate) layer consisting of not less than one foot of soil containing no waste or leachate, that is placed on top of the foundation layer and compacted to attain an hydraulic conductivity of either 1×10^{-6} cm/sec (i.e., 1 ft/yr.) or less, or equal to the hydraulic conductivity of any bottom liner system or underlying natural geologic materials, whichever is less permeable, or another design which provides a correspondingly low through-flow rate throughout the post-closure maintenance

period. Hydraulic conductivity determinations for cover materials shall be as specified in Article 4, Subchapter 2, Chapter 3 of this subdivision [§20310 et seq.], but using water as the permeant, and shall be appended to the closure and post-closure maintenance report. For landfills or portions thereof in which the final cover is installed after July 18, 1997, as part of the final closure plan for the Unit, the discharger shall provide a plan, as necessary [see ¶(a)(4)], for protecting the low-hydraulic-conductivity layer from foreseeable sources of damage that could impair its ability to prevent the throughflow of water (e.g., desiccation, burrowing rodents, or heavy equipment damage).

§20080. SWRCB—General Requirements. (C15: §2510)

20080(4)(b) Engineered Alternatives Allowed—Unless otherwise specified, alternatives to construction or prescriptive standards contained in the SWRCB-promulgated regulations of this subdivision may be considered. Alternatives shall only be approved where the discharger demonstrates that:

(1) the construction or prescriptive standard is not feasible as provided in ¶(c); and

(2) there is a specific engineered alternative that:

(A) is consistent with the performance goal addressed by the particular construction or prescriptive standard; and

(B) affords equivalent protection against water quality impairment.

(c) Demonstration [for ¶(b)]—To establish that compliance with prescriptive standards in this subdivision is not feasible for the purposes of ¶(b), the discharger shall demonstrate that compliance with a prescriptive standard either:

(1) is unreasonably and unnecessarily burdensome and will cost substantially more than alternatives which meet the criteria in ¶(b); or

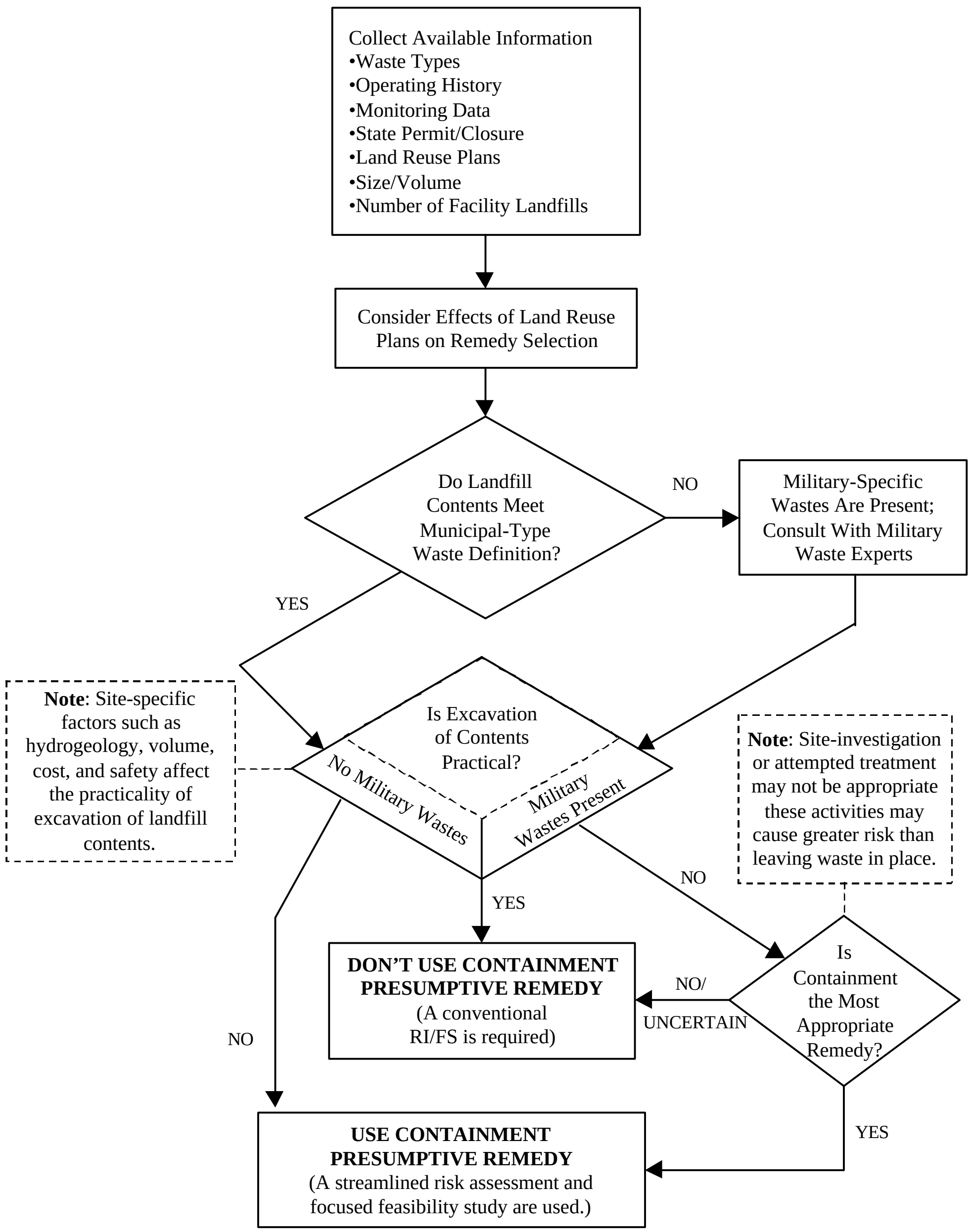
(2) is impractical and will not promote attainment of applicable performance standards.

The RWQCB shall consider all relevant technical and economic factors including, but not limited to, present and projected costs of compliance, potential costs for remedial action in the event that waste or leachate is released to the environment, and the extent to which ground water resources could be affected.

Appendix E

Application of the CERCLA Municipal Landfill Presumptive Remedy to Military Landfills (U.S. Environmental Protection Agency, 1996a)

Presumptive Remedy Selection Chart



Appendix F

Web Sites with Important Innovative Technology Resources

WWW.EPA.GOV/SWERRIMS/

The Office of the Assistant Administrator of EPA for Solid Waste and Emergency Response provides Agency-wide policy, guidance and direction for the Agency's solid waste and emergency response programs, they:

- Develop guidelines and standards for the land disposal of hazardous wastes and for underground storage tanks.
- Furnish technical assistance in the development, management and operation of solid waste activities and analyze the recovery of useful energy from solid waste.
- Are developing and implementing a program to respond to abandoned and active hazardous waste sites and accidental release (including some oil spills) as well as the encouragement of innovative technologies for contaminated soil and groundwater.

WWW.EPA.GOV/SUPERFUND/

EPA's Superfund home page. The link to "Technical Resources" is especially useful.

WWW.EPA.GOV/SWERFFRR/

This Web site is for the Federal Facilities Restoration & Reuse Office (FFRRO). FFRRO's Mission is to facilitate faster, more effective, and less costly cleanup and reuse of federal facilities. By focusing on teamwork, innovation, and public involvement, FFRRO and its Regional counterparts improve environmental cleanup, while protecting and strengthening the conditions of human health, the environment, and local economies.

WWW.CLU-IN.ORG

The Hazardous Waste Clean-Up Information (CLU-IN) Web Site provides information about innovative treatment technology to the hazardous waste remediation community. It describes programs, organizations, publications, and other tools for federal and state personnel, consulting engineers, technology developers and vendors, remediation contractors, researchers, community groups, and individual citizens. The site was developed by the U.S. EPA, but it is intended as a forum for all waste remediation stakeholders.

WWW.RTDF.ORG.

The purpose of the RTDF is to identify what government and industry can do together to develop and improve the environmental technologies needed to address their mutual cleanup problems in the safest, most cost-effective manner. The RTDF fosters public and private sector partnerships to undertake the research, development, demonstration, and evaluation efforts needed to achieve common cleanup goals.

Appendix G

Topical Bibliography

This bibliography contains references that are useful to the study of modern and innovative landfill covers. References are classified by subject although many of them cover more than one subject. The classification was primarily based on words contained in the title. Textbooks, proceedings, design, and construction titles are likely to contain material pertinent to several subjects. The references are divided into the following subjects:

1. Clay Barriers
2. Closure
3. Computer Models
4. Design and Construction
5. General
6. Geosynthetic Components
7. Hydrology
8. Innovative Covers
9. Leachate, Gas and Waste Decomposition
10. Leakage
11. Military
12. Regulations
13. Soil Erosion and Seismic Design
14. Textbooks, Proceedings, Seminars
15. Vegetation

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Glossary of Terms

AERATION, SOIL: The process by which air in the soil is replenished by air from the atmosphere. In a well-aerated soil, the air in the soil is similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and a correspondingly lower percentage of oxygen. The rate of aeration depends largely on the volume, size and continuity of pores in the soil.

AMENDMENT: Any material—such as lime, gypsum, sawdust, or synthetic conditioners—that is worked into the soil to make it more productive. The term is used most commonly for added materials other than fertilizer.

ANIMAL INTRUSION LAYER: Layer in a landfill cover intended to prevent burrowing animals from penetrating the waste or damaging the cover. For example: layer of cobbles or gravel and cobbles.

BARRIER-TYPE COVER: A cover that is designed to prevent water infiltration into the waste by repelling it using very low permeability barriers such as a compacted clay liner, geosynthetic clay liner, flexible membrane or some combination.

BENTONITE: A relatively soft rock formed by chemical alteration of glassy, high silica content volcanic ash. The principal mineral constituent is clay size smectite. It swells extensively in water, has a high specific surface area and it is used in sealing applications in landfills and for sealing wells because it has low hydraulic conductivity when hydrated.

BIODEGRADABLE: Capable of being decomposed by natural biological processes.

BIOINTRUSION LAYER: Layer in a landfill cover used to prevent plant roots and/or burrowing animals from penetrating the waste or otherwise damaging the cover. For example, a layer of cobble or grave.

BULK DENSITY, SOIL: The mass of soil per unit bulk volume, often expressed as g cm^{-3} or megagrams per cubic meter (Mg m^{-3}).

CAP: a name sometimes used for landfill covers**.**

CAPILLARY ACTION (**CAPILLARITY**): The rise or movement of water in a porous media due to capillary forces.

CAPILLARY BARRIER: Landfill cover designed to prevent water infiltration by using the capillary force at the interface between layers of fine over coarse grained materials to increase the water-holding capacity of the fine-grained soil.

CAPILLARY FORCE: See ***CAPILLARY PRESSURE***

CAPILLARY PRESSURE: The difference in pressure across the interface between two immiscible fluid phases (normally air and water) jointly occupying the interstices of a rock. It is due to the tension of the interfacial surface, and its value depends on the curvature of that surface.

CATION EXCHANGE CAPACITY (CEC): The sum of exchangeable bases plus total soil acidity at a specific pH value, usually 7.0 or 8.0. Usually expressed in meq (milliequivalents) per 100 grams of soil.

CELL: Portion of waste in a landfill that is isolated horizontally and vertically from other portions of waste in the landfill by means of a soil barrier.

CHUTE: An open channel for conveying water at high velocity to a lower level.

CLAY: A soil separate consisting of particles <0.002 mm in equivalent diameter.

COBBLE: Rounded or partially rounded stone or mineral fragments between 75 and 250 mm.

COEFFICIENT OF PERMEABILITY: The rate of discharge of water under laminar-flow conditions and at a standard temperature (usually 20°C) through a unit cross-sectional area of a porous medium under a unit hydraulic gradient. Frequently simply termed "permeability" in soil-mechanics usage. See ***PERMEABILITY***.

COMPACTED CLAY LAYER (CCL): Layer in a landfill cover or bottom liner that is composed of clay compacted to prevent passage of water.

COVER MATERIAL: A soil or other suitable material that is used to cover the liner or wastes in a disposal site.

COVER, FINAL: The cover material that is applied at the end of the useful life of a disposal site and represents the permanently exposed final surface of the fill.

DIFFERENTIAL SETTLEMENT: Uneven settlement of landfill cover due to uneven settlement of underlying wastes as decomposition progresses.

DIKE: A barrier to the flow of surface waters formed by a raised embankment.

DUCTILE: Capable of being deformed without failure.

EFFECTIVE DIAMETER: Grain size diameter at which 10% by weight of soil particles are finer and 90% are coarser.

EPIC: Environmental Policy Integrated Climate model. Numerical model that simulates physical processes involved in water movement. Developed by the United States Department of Agriculture.

EROSION: The wearing away of a land surface by moving water, wind, ice, or other geological agents.

EVAPOTRANSPIRATION (ET): The combined processes by which water is transferred from the earth surface to the atmosphere. The evaporation of water from the soil plus transpiration from plants.

FERTILITY (**SOIL**): The relative ability of a soil to supply the nutrients essential to plant growth.

FIELD CAPACITY: The content of water remaining in a soil 2 or 3 days after having been wetted with water and free drainage is negligible. For practical purposes, the water content when soil matric potential is –1/3 atmospheres.

FILTER: A layer or combination of layers of pervious materials designed and installed in such a manner as to provide drainage, yet prevent the movement of soil particles by water flowing through the soil pores.

FLEXIBLE MEMBRANE COVER: Landfill cover which uses flexible membrane material as the primary barrier to water infiltration.

FLEXIBLE MEMBRANE LINER: See ***GEOMEMBRANE***

FOUNDATION: Lowermost layer in a landfill cover. Placed to produce a firm foundation and the proper gradient for overlying layers. Normally compacted to some extent.

GEOCOMPOSITE: Composite of geosynthetic materials or geosynthetic material combined with another material such as clay. For example, a high strength geosynthetic may be combined with a high permeability geosynthetic. See also ***GEOSYNTHETIC CLAY LINER***.

GEOMEMBRANE: A flexible, very low permeability, thin sheet of rubber or plastic material used primarily for linings and covers of liquid or solid storage impoundments, thus serving as a moisture or fluid barrier.

GEONET: Geosynthetic material formed by continuous extrusion of parallel sets of polymeric ribs at acute angles. When material is put under tension, the ribs open to form a highly permeable flow path. Used for drainage in place of (or to enhance) more traditional drainage layers composed of coarse-grained sand or gravel. (also known as geospacers)

GEOSYNTHETIC CLAY LINER: Geocomposite composed of thin layers of bentonite clay sandwiched between two geotextiles or bonded to a geomembrane. Used as water flow barrier.

GEOSYNTHETIC: Any of several synthetic materials used in geotechnical applications including blocking moisture, enhancing drainage and enhancing slope stability. See also ***GEOMEMBRANE, GEONET, GEOTEXTILE.***

GEOTEXTILE: A flexible, porous (to water flow) synthetic fabric used in soil construction for applications such as separation, reinforcement, filtration, or drainage.

GRADATION (**GRAIN-SIZE DISTRIBUTION**) (**PARTICLE-SIZE DISTRIBUTION**) (**SOIL TEXTURE**): Proportion of material of each grain size present in a given soil.

GRADE: 1. The slope of a road, channel, or natural ground. 2. The finished surface of a canal bed, roadbed, top of embankment, or bottom of excavation; any surface prepared for the support of construction like paving or laying a conduit. 3. To finish the surface of a canal bed, roadbed, top of embankment, or bottom of excavation.

GRADIENT: The degree of slope or a rate of change of a parameter measured over distance.

GRAVEL: Unconsolidated granular mineral material of pebble sizes. Rounded or semi-rounded particles of rock ranging from 2 to 75 mm in diameter.

GROUND COVER: Grasses or other plants grown to keep soil from being blown or washed away.

GROWING SEASON: The period and/or number of days between the last freeze in the spring and the first frost in the fall for the freeze threshold temperature of the crop or other designated temperature threshold.

GULLY: A channel resulting from soil erosion and caused by the concentrated but intermittent flow of water usually during and immediately following heavy rains. A gully is sufficiently deep that it would not be obliterated by normal tillage operations, whereas a rill is of lesser depth and would be smoothed by ordinary farm tillage.

HAZARDOUS WASTE: A solid waste or combination of solid wastes, which because of its quantity, concentration or physical, chemical, or infectious characteristics may:

- Cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or Pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed (Public Law 94-580, 1976).

HEAD: A measure of the energy that water possesses by virtue of its elevation, pressure, or velocity. The components Elevation Head, Pressure Head, and Velocity Head combine to make Total Head. All heads are expressed in linear units, e.g. feet. At all points in a body of water at rest, the total head (equals static head) is the same, pressure heads exactly compensating elevation heads, and velocity heads being zero. Water flows spontaneously from paints of higher to points of lower total head.

HELP: Hydrologic Evaluation of Landfill Performance. Numerical model used to predict percolation of water through landfill cover and leachate generation. Developed by US Army Corps of Engineers for the US Environmental Protection Agency.

HORIZON (**SOIL HORIZON**): One of the layers of the soil profile, distinguished principally by its texture, color, structure, and chemical content.

- **A HORIZON**: The uppermost layer of a soil profile. Usually contains remnants of organic life.
- **B HORIZON**: The layer of a soil profile in which material leached from the overlying A horizon is accumulated.
- **C HORIZON**: Parent material from which the overlying soil profile has been developed.

HYDRATED: Combined with water.

HYDRAULIC CONDUCTIVITY: Term used in groundwater hydrology and soil science. Equivalent to Coefficient of Permeability.

IMPERMEABLE: Not permitting passage of a fluid or a gas through its substance.

IN SITU: In its natural or original position.

INDICATOR PLANTS: Plants characteristic of specific soil or site conditions.

INDUSTRIAL WASTE: Waste from industrial processes, as distinct from municipal solid waste.

INFILTRATION RATE (**INFILTRATION CAPACITY**): A soil characteristic determining the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water. It has the dimensions of velocity.

INFILTRATION: The downward entry of water into the soil.

INNOVATIVE COVER: A cover that meets regulatory requirements for results (for instance: limits water infiltration, isolates wastes…) while not using specific design elements mandated by those regulations or customarily used

LEACHATE: Liquid that has percolated through or drained from a material (such as waste in a landfill) and contains soluble, partially soluble, or miscible components removed from such material.

LEACHING: The removal from soil or waste of the more soluble materials, in solution, by percolating waters.

LIFT: A single layer of compacted soil. Lift thickness depends on soil and degree of compaction needed (also termed “course”).

LINER: A layer of emplaced material beneath a surface impoundment or landfill which is intended to restrict the escape of waste or its constituents from the impoundment or landfill. May include reworked or compacted soil and clay, asphaltic and concrete materials, spray-on membranes, polymeric membranes, chemisorptive substances, or any substance that serves the above stated purpose.

LOAM: Soil material that contains 7 to 27 percent clay, 28 to 50 percent silt and <52 percent sand.

LYSIMETER: A device used to measure the quantity or rate of water movement through or from a block of soil or other material, such as solid waste, or used to collect percolated water for qualitative analysis.

MATRIC POTENTIAL: The amount of work that must be done to permanently move (without change in temperature) an infinitesimal quantity of water from a specified source to a specified destination. Also known as soil water potential.

MIL: Unit of length, equal to .001 inch or .0254 mm.

MIXED WASTE: Waste composed of any combination of the following: municipal, industrial, hazardous or radioactive.

MOISTURE CONTENT: See ***WATER CONTENT***.

MONOFILL COVER (MONOCOVER): Relatively simple single soil layer landfill cover. Soil may or may not be compacted. Used in arid or semi-arid climate.

MULCH: A natural or artificial layer of plant residue or other materials, such as sand or paper, on the soil surface.

MUNICIPAL SOLID WASTE: Solid waste collected from residential and commercial sources in bins and other large containers.

NATIVE SPECIES: A species that is part of an area's original fauna or flora.

NUTRIENTS: 1. Elements, or compounds, essential as raw materials for organism growth and development, such as carbon, oxygen, nitrogen, phosphorus, etc. 2. The dissolved solids and gases of the water of an area.

PARENT MATERIAL: The unconsolidated and more or less chemically weathered material (normally rock) from which soil is developed.

PARTICLE SIZE: The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods.

PEBBLE: Rounded or semi-rounded rock or mineral fragment between 2 and 75 mm in diameter. Fragment size found in gravel.

PERCHED WATER TABLE: A water table usually of limited area maintained above the normal free water elevation by the presence of an intervening relatively impervious confining stratum.

PERCOLATION: Downward movement of water through soil. Especially, the downward flow of water in saturated or near-saturated soil at hydraulic gradients of the order of 10 or less.

PERENNIAL PLANT: A plant that normally lives three or more years.

PERMEABILITY: Capability of a material to transmit fluid through its substance.

POLYVINYL CHLORIDE (PVC): A synthetic thermoplastic polymer prepared from vinyl chloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens; flexible forms used in manufacture of sheeting.

PORE WATER PRESSURE: See ***STRESS***

PORE: A small to minute opening or passageway in a rock or soil; an interstice.

POROSITY: The ratio, usually expressed as a percentage, of the volume of voids of a given soil mass to the bulk (total) volume of the soil mass.

PREFERENTIAL FLOW: The process whereby free water and its constituents move by preferred pathways through a porous medium (such as along the interface between soil and plant roots, cracks, or other channels).

REVEGETATION: Plants or growth that replaces original ground cover following land disturbance.

RILL: Small intermittent water channel, usually only several centimeters deep. Normally formed by erosion of recently cultivated soils.

RIPRAP: Broken rock, cobbles, or boulders placed on earth surfaces, such as the face of a dam or the bank of a stream, for protection against the action of water waves. Also applied to brush or pole mattresses, or brush and stone, or other similar materials used for soil erosion control.

ROOT ZONE: The part of the soil that is penetrated or can be penetrated by plant roots.

RUNOFF: That portion of precipitation or irrigation water that drains from an area as surface flow.

SAND: Unconsolidated granular mineral material ranging from 0.05 to 2 mm in diameter.

SATURATION: The point at which all voids in a material are filled with water.

SEED: The fertilized and ripened ovule of a seed plant that is capable, under suitable conditions, of independently developing into a plant similar to the one that produced it.

SEEPAGE: Slow movement of water through soil.

SEMI-ARID: Marked by light annual rainfall and capable of sustaining only short grasses and shrubs.

SHEAR STRENGTH: The maximum resistance of a material to shearing stresses.

SHRUB: A woody perennial plant differing from a tree by its low stature and by generally producing several basal shoots instead of a single bole.

SILT (**SILT SOIL**): Soil material that contains 80% or more silt and < 12% clay.

SLOPE: Deviation of a surface from the horizontal expressed as a percentage, by a ratio, or in degrees. In engineering, usually expressed as a ratio of horizontal to vertical change. See also ***GRADE***.

SOD: A closely knit groundcover growth, primarily of grasses.

SOIL PROFILE (**PROFILE**): Vertical section of a soil, showing the nature and sequence of the various layers, as developed by deposition or weathering, or both.

SOIL SCIENCE: The study of soils including soil formation, classification and mapping; physical, chemical, biological and fertility properties of soils; and these properties in relation to the use and management of soils.

SOIL STABILIZATION: Chemical or mechanical treatment designed to increase or maintain the stability of a mass of soil or otherwise to improve its engineering properties.

SOIL: In engineering, sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter. In soil science, the unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of plants.

SOLAR RADIATION: The total electromagnetic radiation emitted by the sun.

STRESS: Intensity of force. The force per unit area acting within a mass.

- **EFFECTIVE STRESS** (**EFFECTIVE PRESSURE**) (**INTERGRANULAR PRESSURE**): The average normal force per unit area transmitted from grain to grain of a soil mass. It is the stress that is effective in mobilizing internal friction.
- **NEUTRAL STRESS** (**PORE PRESSURE**) (**PORE WATER PRESSURE**): Stress transmitted through the pore water (water filling the voids of the soil).
- **NORMAL STRESS**: The stress component normal to a given plane.
- **SHEAR STRESS** (**SHEARING STRESS**) (**TANGENTIAL STRESS**): The stress component tangential to a given plane.

STUBBLE: The basal portion of plants remaining after the top portion has been harvested; also, the portion of the plants, principally grasses, remaining after grazing is completed.

SUBSIDENCE: Settling or sinking of the land surface due to any of several factors, such as decomposition of organic material, consolidation, drainage, and underground failure.

SUBSOIL: The B horizons of soils with distinct profiles. In soils with weak profile development, the subsoil can be defined as the soil below the plowed soil (or its equivalent of surface soil), in which roots normally grow. Although a common term, it cannot be defined accurately.

TERRACE: An embankment or combination of an embankment and channel constructed across a slope to control erosion by diverting surface runoff water.

TILLAGE: The mechanical manipulation of the soil profile.

TRANSPIRATION: The process by which water in plants is transferred to the atmosphere as water vapor.

Unsat-H: Unsaturated Water and Heat Flow. A numerical water balance model developed by Pacific Northwest Laboratories.

WATER BALANCE: The sum of water in and passing through a landfill including storage of moisture in the landfill, input of moisture including precipitation and surface run-on, output of moisture including leachate, surface runoff, ET.

WATER CONTENT: In soil mechanics, the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles. In soil science, the amount of water lost from the soil after drying it to constant weight at 105°C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil.

WATER TABLE: The surface between the zone of saturation and the zone of aeration; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere.

WATERLOGGED: Saturated with water; soil condition where a high or perched water table is detrimental to plant growth, resulting from over-irrigation, seepage, or inadequate drainage; the replacement of most of the soil air by water.

List of Acronyms

ARAR	Applicable or Relevant and Appropriate Requirement
CAMU	Corrective Action Management Unit
CCL	Compacted clay layer
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CIWMB	California Integrated Waste Management Board
CLU-IN	Hazardous Waste Clean-Up Information
COC	Contaminant (or chemical) of concern
DOD	Department of Defense
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate
ESTCP	Environmental Security Technology Certification Program
ET	Evapotranspiration
ETI	Environmental Technology Initiative
ETV	Environmental Technology Verification Program
FFRRO	Federal Facilities Restoration & Reuse Office
FMC	Flexible Membrane Cover
GCL	Geosynthetic Clay Layer
GLEAMS	Groundwater Loading Effects from Agricultural Management Systems
GM	Geomembrane
HDPE	High-Density Polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
HW	Hazardous Waste
K	Saturated Hydraulic Conductivity
LEA	Local Enforcement Agency
LEL	Lower Explosive Limit
LFG	Landfill Gas
LLDPE	Linear Low-Density Polyethylene
MBALANCE	Water Balance Analysis Program
MSW	Municipal Solid Waste
MSWLF	Municipal Solid Waste Landfill
NCERQA	National Center for Environmental Research and Quality Assurance
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NELP	Naval Environmental Leadership Program
NETTS	National Environmental Technology Test Sites Program
NPL	National Priorities List

OSWER	Office of Solid Waste and Emergency Response
PCL	Protective Concentration Level
POE	Point of Exposure
PP	Polypropylene
PRC	Public Resources Code
PRDA	Program Research and Development Announcement
PST	Petroleum Storage Tank
PVC	Polyvinyl Chloride
RB/PB	Risk-Based/Performance-Based
RBEL	Risk-Based Exposure Limit
RCI	Rapid Commercialization Initiative
RCRA	Resource Conservation and Recovery Act
ROA	Research Opportunity Announcement
ROD	Record of Decision
RPM	Remedial Project Manager
RTDF	Remediation Technologies Development Forum
RWQCB	Regional Water Quality Control Board
SARA	Superfund Amendments and Reauthorization Act
SBIR	Small Business Innovative Research Program
SERDP	Strategic Environmental Research and Development Program
SITE	Superfund Innovative Technology Evaluation Program
SW	Solid Waste
SWRCB	State Water Resources Control Board
TAC	Texas Administrative Code
TRRP	Texas Risk Reduction Program
UIC	Underground Injection Control
UNSAT-H	Unsaturated Soil Water and Heat Flow
USDA	U.S. Department of Agriculture
USLE	Universal Soil Loss Equation
VCP	Voluntary Cleanup Program
VOC	Volatile organic compound